TAY BRIDGE DISASTER.

REPORT OF THE COURT OF INQUIRY,

AND

REPORT OF MR. ROTHERY,

UPON THE

Circumstances attending the Fall of a Portion of the Tay Bridge on the 28th December 1879.

Presented to both Houses of Parliament by Command of Her Majesty.

LONDON
PRINTED BY GEORGE EDWARD EYRE AND WILLIAM SPOTTISWOODE,
PRINTERS TO THE QUEEN'S MOST EXCELLENT MAJESTY.
FOR HER MAJESTY'S STATIONERY OFFICE.

1880.

[C.—2616.] *Price 9d.*

Whereas by The Regulation of Railways Act, 1871, it is provided that the Board of Trade may direct an inquiry to be made by an Inspector into the cause of any accident of which notice is for the time being required by or in pursuance of the said Act to be sent to the Board of Trade; and where it appears to the Board of Trade, either before or after the commencement of any such inquiry, that a more formal investigation of the accident, and of the causes thereof, and of the circumstances attending the same, is expedient, the Board of Trade may, by order, direct such investigation to be held:

And whereas it is by the same Act further provided that the Board of Trade may by the same or any subsequent order direct the County Court Judge, Stipendiary Magistrate, Metropolitan Police Magistrate, or other person or persons named in the same or any subsequent order to hold the same:

Now therefore the Board of Trade, in pursuance of the powers conferred upon them by the said recited Act, do hereby direct a formal investigation to be held into the causes of, and circumstances attending, an accident which took place on the Railway Bridge crossing the Firth of Tay on the North British Railway on the twenty-eight instant, and do further, in pursuance of the powers conferred by the said recited Act, hereby appoint and direct Henry Cadogan Rothery, Esquire, Wreck Commissioner; Colonel William Yolland, Chief Inspector of Railways; and William Henry Barlow, Esquire, President of the Institute of Civil Engineers, to hold the said formal investigation.

Given under my hand this thirty-first day of December, 1879.

(Signed) T. H. FARRER,
DG (L.S.) Secretary to the Board of Trade.

TAY BRIDGE.

TO THE RIGHT HONOURABLE THE PRESIDENT OF THE BOARD OF TRADE.

SIR, London, 30th June 1880.

HAVING by your order of the 31st December last been directed to hold a formal investigation under the provisions of the "Regulation of Railways Act, 1871," "into "the causes of and the circumstances attending an accident which took place on "the railway bridge crossing the Firth of Tay, on the North British Railway on the "twenty-eighth" of that month, we at once proceeded to Dundee for the purpose of making a personal inspection of the bridge and of examining any witnesses who would give evidence as to the circumstances attending the accident whilst the facts were still fresh in their memories. The inquiry was opened on Saturday, the 3rd, and was continued on Monday and Tuesday, the 5th and 6th of January, Mr. Trayner appearing for the Solicitor of the Board of Trade and Mr. Balfour for the North British Railway Company. Having by that time examined all the witnesses whom the parties were then prepared to produce before us, as well as having made an inspection of the bridge, we adjourned the further hearing of the case in order to allow time to procure such information as to the details of its construction, and as to its present state and condition, as seemed to be necessary for the purpose of our inquiry. With this view we appointed Mr. Henry Law, a member of the Institute of Civil Engineers, with directions to make a minute and careful examination of the bridge, and to report to us fully thereon, as well as on the probable cause of the accident, and to select specimens of the cast and wrought iron, also portions of the cross bracing and its fastenings, and of the connecting bolts of the columns, &c., to be subjected to test at Mr. Kirkaldy's establishment at Southwark. We also called upon the railway company to furnish us with the particulars of the weight, strength, and dimensions of the various parts of the structure. Photographs of the piers, of portions of the fallen girders and permanent way, and of the remains of the engine and carriages were ordered to be prepared and laid before us.

Whilst waiting for Mr. Law's report, and for the answers of the Railway Company to the questions addressed to them, we were told that there were a number of witnesses at or near Dundee who could give important information as to the condition of the bridge before the accident. We accordingly again went to Dundee, and between Thursday, the 26th of February, and Wednesday, the 3rd of March last, a number of witnesses were examined, mainly with reference to alleged defects of workmanship and inferior quality of materials used in the bridge, and also as to the speed at which the trains crossed it.

At length Mr. Law's report, dated the 9th of April, as well as the answers from the Railway Company, having been received, and the case appearing to be otherwise ready for hearing, the inquiry was resumed at Westminster on Monday the 19th of April, and between that day and Saturday the 8th May, when it was brought to a close, a large number of witnesses were examined. On this occasion Sir Thomas Bouch, the engineer, and Messrs. Hopkins, Gilkes, & Co., the contractors, appeared by separate counsel; Mr. Bidder representing the former, and Messrs. Webster and Macrory the latter, Mr. Trayner and Mr. Balfour appearing, as before, for the Solicitor of the Board of Trade and the Railway Company respectively. Reports were also brought in from Mr. Kirkaldy, showing the results of the tests.

From the information which has been laid before us, it would seem that a company having been formed to build a bridge, and an Act obtained for the purpose, a contract was on the 1st of May 1871 entered into with Messrs. De Bergue & Co. to undertake the work.

In consequence of the illness of Mr. Charles de Bergue, the leading partner in the contractor's firm, and his inability to attend to business, it became necessary to transfer the contract to other hands. This was accordingly done, and on the

26th of June 1874, another contract was entered into with Messrs. Hopkins, Gilkes, & Co., of Middlesborough, to complete the work. The new contractors agreed to take over from Messrs. de Bergue the whole of the existing staff and plant, as well as a foundry which had been erected at Wormit, near the southern end of the bridge, where a large portion of the castings required for the works were made.

The bridge was designed by Sir T. Bouch, and the supervision of its construction was entrusted to him up to the period of its being opened for traffic. He was subsequently charged by the North British Railway Company with its maintenance, and remained so charged up to the date when the structure fell.

Description of the Bridge.

I. The bridge, as originally designed, and as referred to in the specifications, had piers of brickwork and spans of 200 feet of clear water space in that portion of it which forms the subject of this Inquiry; but in consequence of difficulties with the foundations, Sir T. Bouch altered the spans to 245 feet, excepting two, which were made 227 feet; and he also altered the piers from brickwork to ironwork above high-water level, in order to lessen the weight on the foundations, and to obtain the best distribution of weight and material which the circumstances permitted. It should be added that the proposal to alter the piers from brick to iron was made before the contract was entered into with Messrs. Hopkins, Gilkes, & Co., but the final designs were not settled until afterwards; and there is a letter from Mr. Gilkes to Sir Thomas Bouch, dated the 9th of June 1875, in which he speaks of the proposed "enlarge-" "ment of the spans and certain alterations of the piers," which he states had, after "long and careful consideration," been at length decided on. From this time the work progressed with great rapidity, a large number of men being constantly employed both on the bridge itself and at the Wormit foundry; and although some delay occurred from the fall during a heavy gale of wind, of two of the large iron girders whilst they were being raised into their positions, together with the piers on which it was proposed to place them, the bridge was completed, if not within, at all events very soon after, the stipulated time.

The bridge was 3,465 yards in length. The superstructure was of wrought-iron lattice girders, except one span on the northern portion, which was crossed by bow-string girders.

Each lattice girder was complete in itself, but they were connected together so as to form continuous girders extending over groups of four, five, and six spans.

The spans of the bridge varied from 245 feet to 29 feet. The piers were 85 in number, of which the first 14 were of brick, the remainder being formed above high-water level of tiers of cast-iron columns bolted together vertically by bolts and nuts, and connected together latterally by means of cross bracing and struts of wrought iron. The number of columns in position on each pier varied from three to six. Those under the largest spans were formed of six columns, bolted to base pieces, which were bedded in stone. The lower portions of these piers consisted of concrete, brickwork, and masonry, their construction being accomplished by means of iron caissons which were left in forming part of the permanent work.

Commencing from an abutment on the south shore, the bridge curved for the first three spans to the left until it came at right angles to the course of the river, which here runs nearly due east and west; it was then straight to pier 53, whence it curved sharply off to the right with a radius of 20 to 22 chains, until it finally reached het north shore. For the first three spans after leaving the south shore, the roadway fell slightly; from piers 3 to 6 it was level; it then rose on a gradient of 1 in 353 until it reached pier No. 29; from 29 to 30 the gradient was 1 to 490; it was then level for six spans, and at pier 36 it began to fall, the gradient from 36 to 37 being 1 in 130, after which the fall was 1 in 74 until it reached the north shore. The summit level of the bridge, 88 feet above high-water mark, extended from pier 30 to pier 36, whence it fell gently to the south, but rapidly towards the north, the land on the south shore being much higher than on the north shore.

At piers 28 and 41 the girders were raised so that the lower booms were on a level with the upper booms of the girder south of 28 and north of pier 41; the object was to give additional headway to passing vessels, it being here that the bridge crossed the navigable part of the river. The roadway from the south shore to pier 28, and again from 41 to the north shore, being carried on the upper booms, and therefore above and on the top of the girders, whilst between piers 28 and 41 it was carried on the lower booms, inside the girders. It was this portion, called the high girders, which fell, and it is therefore to this part of the bridge that attention must be more particularly directed.

The high girders extended over 13 spans, namely, 11 of 245 feet each, and two of 227 feet each, making a total of 3,149 feet. This portion was divided into three sections or groups, the first, counting from the south, contained five spans of 245 feet each; the second, of four spans, two of 245 and two of 227 feet each; and the third, of four spans, all of 245 feet each. There were expansion joints on piers 28, 33, 37, and 41; fixed bearings on piers 31, 35, and 39; and roller bearings on the seven remaining piers 29, 30, 32, 34, 36, 38, and 40.

The girders in this part of the bridge were 27 feet high, and 14 feet 10 inches apart from centre to centre. The two upper booms were braced together at intervals by wrought-iron struts and diagonal ties; but the lower booms, which carried the permanent way, were connected by transverse wrought-iron girders, placed about 5 feet 5 inches apart, rivetted to the upper side of the bottom booms. On the whole, the girders appear to have been carefully proportioned to the strains which they had to bear; and as there is no reason to suppose that the casualty was in any way due to defects in the girders, it is not necessary to describe them more fully.

Assuming the permanent way on the fallen part of the bridge to be similar to that on the part left standing, it was strongly constructed and properly fish-jointed, and had strong guard rails also fish-jointed, and was kept in very good order.

The piers which supported the high girders were of peculiar construction, the nature of which is fully described in Mr. Law's report; and as they were evidently the first portion of the structure that yielded from some cause, it becomes necessary to refer to them more in detail. The foundations were formed by constructing wrought-iron caissons 31 feet in diameter, which, having been lined with 18 inches of brick-work, were floated out and sunk in their proper places. This was an extremely difficult operation, but appears in every instance to have been successfully performed. After sinking the caissons as low as was deemed necessary, the centre was filled up with concrete, and upon this was built an hexagonal-shaped pier, measuring 27 feet 6 inches long, and 15 feet 6 inches broad. The lower part of this pier was made of concrete faced with brick, and was surmounted by four courses of stone backed by concrete. On this pier was placed, at the angles of the hexagon, six cast-iron base pieces, 2 feet in height, and secured to the pier by holding-down bolts, $1\frac{3}{4}$ inches in diameter, passing through two courses of stone, each 15 inches in thickness.

Upon these six base pieces were fixed six cast-iron columns; piers 28 and 41 consisted of six tiers of columns and those from 29 to 40 inclusive consisted of seven tiers.

The columns were cast with flanges which were fastened to each other and to the base pieces by eight connecting bolts $1\frac{1}{8}$ inches in diameter. They had also an inner projecting rim or spigot about $\frac{3}{4}$ of an inch deep, fitting into a corresponding recess in the adjoining column.

The columns after they were erected were filled with Portland cement concrete poured in from the top.

The cross bracing of the piers consisted of wrought-iron flat tie bars $4\frac{1}{2}'' \times \frac{1}{2}''$ in section, fastened at their upper extremity by means of wrought-iron pins passing through lugs cast with and forming part of the columns; at their lower extremities there were two wrought-iron sling plates fastened by similar wrought-iron pins to other lugs, cast in like manner on the lower part of the columns adjacent to the flanges. The sling plates, $\frac{3}{8}$ of an inch thick, which were of equal width with and placed on each side of the tie bars, were connected to them by gibs and cotters, by means of which the cross bracing was tightened up and brought to its bearings. The horizontal struts consisted of two channel irons, bolted by two bolts at each end to other lugs similarly cast with the columns. The channel irons did not abut against the sides of the cast-iron columns.

Of the six columns forming each of these hexagonal piers the two extreme east and west columns were of 18 inches external diameter, $1\frac{1}{4}$ inches thick, placed 21 feet 10 inches apart from centre to centre, and these had an inclination of 12 inches towards the centre in a plane at right angles to the line of the bridge. The four inner columns, which were 15 inches diameter and placed at a distance from east to west of 9 feet 10 inches, and from north to south of 12 feet, had each an inclination inwards of the same amount. The effect of this inclination was that, whilst the distance of the outer column from the line joining the two next inner columns was 6 feet at the base, the distance at the tops of the columns was only 5 feet, and whilst the two inner columns were 12 feet apart at their bases, the tops were only 10 feet apart. The six columns formed two triangular groups, each consisting of one outer and two inner columns, the bases of the triangles being parallel to the line of the bridge.

At the top of the piers, each group of three columns was surmounted by a strong wrought-iron box girder L-shaped in plan; and above each of these L-shaped girders was a wrought-iron cellular table, running north and south in the direction of the bridge, and placed immediately under the longitudinal main girders which formed the sides of the bridge. Upon the upper side of the cellular table was bolted a strong cast-iron plate, a similar plate being bolted to the under side of the longitudinal main girder of the bridge, and between these two plates were placed cast-iron rollers, each 2 feet long and 5 inches in diameter, with flanges of three-quarters of an inch deep, except at the piers, where there were fixed bearings, at which piers the longitudinal main girder was attached directly to the cellular table by bolts and nuts.

The two main girders, between which the permanent way was carried, were supported upon the L-shaped box girders in such a position that about one half of the weight of each main girder was borne by the outer column (18 inches in diameter) of each group of three columns, and the other half rested on the two inner columns (15 inches in diameter). The two L-shaped box girders were not connected together, and did not form one entire girder across the top of the piers; but the columns were connected together at the top of the piers by the struts of the cross bracing.

The strength given to the columns as designed was sufficient for the duty they had to perform in bearing vertical weights evenly distributed.

Imperfection of workmanship and fitting.

II. In regard to imperfection of workmanship and fitting, it appears, that as the substitution of iron for brick piers in this part of the work was made after the contract was let, there are no clauses in the specification describing the class of workmanship to be employed in them.

The stipulation in the general specification, which requires all the holes in the flanges of the columns to be drilled, was not carried out in this part of the work as regards the holes in the flanges of the 18-inch columns. The holes in the lugs on the columns were all cast and left conical, instead of being drilled, thus causing the pins to have unequal bearings. Some of the sling plates which were made or altered at the works were roughly formed.

Imperfection of workmanship was also found in the bolt holes of the struts, and as the struts did not abut against the columns, as in our opinion they ought to have done, their action in these cases depended on the friction or resistance to movement made by bolting the channel irons tightly together, and bearing hard against the lugs.

The columns after the accident were found in some instances to be of unequal thickness, and to have other defects of casting, and it was probably due to the sluggish character of the metal and the manner in which the columns were cast, that the castings of the lugs did not always turn out sound, as out of 14 tie bars attached to lugs, tested in London, four showed unsoundness to a greater or less extent at the lugs.

It is stated in evidence that, in some cases where lugs had turned out imperfect in casting, other lugs or portions of lugs were added by a process termed "burning on." This is admitted to have been done; but it is denied that any columns so treated were used in the permanent structure, and, although a large number of broken lugs are visible in the ruins of the fallen bridge, none were found during Mr. Law's examination, nor have been otherwise brought to our notice, which appear to have been subjected to this most objectionable and dangerous process.

Official inspection of the bridge.

III. The bridge was inspected by General Hutchinson on the 25th, 26th, and 27th February 1878, at which time it was all finished and painted. During this inspection he subjected the bridge to various tests, and among others he caused six locomotives coupled together, each weighing 73 tons, to pass over the bridge at a speed of 40 miles per hour. The behaviour of the bridge under these tests appears to have been satisfactory, there having been only a moderate deflection in the girders, a small degree of tremor, and no indication of looseness in the cross bracing.

On the 5th of March he reported that he saw "no reason why the Board of Trade should object" to the bridge being used for passenger traffic; but that it would "not be desirable that trains should run over the bridge at a high rate of speed," and suggested "25 miles an hour as a limit, which should not be exceeded," adding that "very careful attention will be required to ascertain from time to time that no scouring action is taking place in the foundations," and that he should wish, if possible, to have an opportunity of "observing the effects of a high wind when a train of carriages is running over the bridge." Some delay occurred in opening the

bridge owing to the approaches on either side not being completed, but on the first day of June 1878 it was open for passenger traffic, and from that time trains continued to run regularly across it until the evening of the 28th of December last, when the disaster which we are now about to describe occurred.

Circumstances attending accident.

IV. The train previous to that which fell with the bridge left Tayport about 5.50 p.m., and passed over the bridge about 6.5 p.m. The engine-driver did not notice anything unusual in the travelling of this train, but the guard, Shand, and two men who were with him, saw sparks of fire coming from the wheels of the carriages. Shand put on his break and showed his red light, but it was not seen by the driver; he also examined his train at the Dundee Station, but finding nothing wrong made no report.

The train from Edinburgh which fell with the bridge arrived in due course at St. Fort Station, and there the tickets of the passengers for Dundee were as usual collected. We were told by the ticket collectors that there were at that time in the train 57 passengers for Dundee, five or six for Broughty Ferry, five for Newport, two season ticket holders, the engine driver, stoker, and guard of the train, and two other guards, making 74 or 75 persons altogether. The tickets having been collected, the train proceeded on its course, leaving St. Fort Station at 7.8 p.m., and on approaching the cabin which stands at the southern end of the bridge, the speed was slackened to about three or four miles an hour to enable the engine driver to take the baton or train staff, without which he is not allowed to cross the bridge. On receiving the baton, steam was again turned on, and the train passed on to the bridge, upon which the signalman, Thomas Barclay, signalled to the north cabin signalman, the time according to the entry in his book, being exactly 13 minutes after 7 o'clock. It was then blowing a strong gale from about W.S.W., and therefore almost directly across the bridge; there was a full moon, but it was quite dark, owing to the face of the moon being obscured by clouds. It seems that a surface man in the employment of the North British Railway Company, named John Watt, had gone to keep Barclay company, and was in the cabin when the train passed; and whilst Barclay was attending to his duties, entering the time in his book and making up the stove fire, Watt was watching the train through the window in the cabin door, which looks north along the line. According to Watt, when the train had got about 200 yards from the cabin, he observed sparks flying from the wheels; and after they had continued about three minutes, there was a sudden bright flash of light, and in an instant there was total darkness, the tail lamps of the train, the sparks, and flash of light, all, he said disappearing at the same instant.

The portion of the bridge which fell consisted of three sets of continuous girders, covering respectively five spans, four spans, and four spans, making thirteen spans altogether.

These continuous girders rested on rollers on all their piers except one near the centre of each set, and to these central piers they were fixed. In the accident which took place, the girders turned over and fell on their sides, each girder becoming slightly curved, the centre portion being furthest from the piers, and the ends curving towards the piers, some irregularity showing itself in the curve at the first fallen pier from the south end.

The train was found partly in the fourth and partly in the fifth spans from the south end, so that, although it had travelled some distance along the first set of continuous girders, it never reached its northern extremity. The engine and tender were found lying on their sides on the eastern girders. The train consisted (counting from the engine) of one third class, one first class, two third class, one second class, and the guard's van. The second class carriage and the guard's van had their bodies and all their upper portions entirely destroyed; their lower frames were greatly damaged, and the axles of these vehicles as well as those of all the other carriages were bent.

The throttle valve of the engine was full open, and the reversing lever standing in the sixth notch from full forward gear, or in the third notch from the centre. The train was partly fitted with the Westinghouse break, but there was no appearance of its having been put on, and the conclusion to be drawn from these facts is that neither the driver or fireman had any warning of the accident which took place.

Wind pressure.

V. It appears in the evidence that about the time Sir T. Bouch considered the altered designs of the Tay Bridge, he had been preparing plans for a bridge over the Firth of Forth for another company. This bridge being of unprecedented magnitude as regards its spans, and several railway companies being interested in its construction,

other engineers, viz., Sir J. Hawkshaw, Mr. Bidder, Mr. T. Harrison, and Mr. Barlow were consulted; and it was remitted to Mr. Barlow and Dr. Pole to carry out the detailed investigation of the design. It further appears that these gentlemen, not being satisfied with their own judgment upon the question of wind pressure, consulted the Astronomer Royal, who put his opinion into writing in a letter from which the following is an extract:—"We know that upon very limited surfaces, and for very "limited times, the pressure of the wind does amount sometimes to 40 lbs. per "square foot, or, in Scotland, probably to more. So far as I am aware, our positive "knowledge, as derived from instrumental record, goes no further; but in studying "the registers it is impossible not to see that these high pressures are momentary, "and it seems most probable that they arise from some irregular whirlings of the air "which extend to no great distance, I should say certainly to no distance comparable "to the dimensions of the proposed bridge; and I think that the fairest estimate of "the pressure on the entire bridge would be formed by taking the mean of the "recorded pressures at one point of space for a moderate extent of time as repre-"senting the mean pressures on a moderate extent of space at one instant of time. "Adopting this consideration, I think we may say that the greatest wind pressure to "which a plain surface like that of the bridge will be subjected in its whole extent "is 10 lbs. per square foot."

Furnished with this opinion, Messrs. Barlow and Pole report:—"We entirely "concur in this opinion, which we consider highly authoritative and valuable, and we "may therefore safely adopt 10 lbs. per square foot as the side pressure due to the "wind for which Mr. Bouch has to provide. We may now describe the means "which Mr. Bouch has adopted to provide against this side pressure:—The side "surface of each span exposed to the wind (but making allowance for some parts "which may be assumed to bear directly on the piers) is given by Mr. Stewart at "about 14,000 superficial feet. This is for one surface only, *i.e.*, the one first exposed "to the wind; but behind this there are three other similar surfaces, one about "15 feet away, the second about 120 feet away, and the third 135 feet away. The "wind must rush past these after passing the first one; and although each will be "no doubt, to a certain extent, in shelter from those in front of it, we cannot "suppose that they will be free from the wind's action. Possibly it would be a fair "estimate to double the surface of the front face, but as an outside estimate we have "taken three times, or 42,000. To this has to be added 8,000 feet for two trains "which may be on the bridge, giving 50,000 square feet of surface exposed to the "horizontal action of the wind. Allowing, therefore, 10 lbs. per square foot, we "get a force of about 225 tons." Their conclusions, so arrived at, were adopted in the report signed by Sir J. Hawkshaw, Mr. Bidder, Mr. T. Harrison, and Mr. Barlow.

Sir T. Bouch states that this report influenced his mind, and that in consequence he did not consider it necessary to make any special provision for wind pressure in the Tay Bridge.

But we think he must have misunderstood the nature of that report, for as it pointed out that the pressures in gusts of wind amounted to 40 lbs. or more, it was obviously necessary to provide for the pressures so arising in each of the spans of the Tay Bridge, and although the limited area of these gusts is described as not being at all comparable to that of the Forth Bridge of 1,600 feet span, yet they might in effect be equal to the whole area in the 245 feet spans of the Tay Bridge, and their operation might take place upon any of the spans.

It must not be understood, however, that we express an opinion as to the sufficiency of a provision for only 10 lbs. of wind pressure in a large span of 1,600 feet. It may represent an amount of force which, as applied to the whole surface, would rarely be exceeded, but after hearing the evidence given at this inquiry it occurs to us as possible that two or more gusts might act simultaneously on so large a span, or there might be a wind gust of unusual width.

Evidence on wind pressure.

VI. With a view to obtain information on the subject of wind pressure from the most authentic sources, we applied to the Astronomer Royal, to Professor Stokes, and to Mr. R. H. Scott, the secretary to the Meteorological Council, and from the evidence given by these gentlemen we learn the following particulars.

It appears that the term wind pressure, as now usually employed, means the force produced by the wind when acting against and at right angles to a flat plate or disc; and it is expressed in pounds per square foot. It can be arrived at directly by the instrument known as Osler's anemometer, which consists of a flat plate or board acting against a spring with a recording apparatus, that exhibits the degree of

compression produced on the spring by the action of the wind, or it can be deduced approximately from the "*standard pressure*," by which term is meant the height at which a column of fluid is maintained or supported by wind pressure, or it can be deduced approximately from the velocity of the wind, due allowance being made for the height of the barometer and thermometer, and the hygrometrical state of the air at the time, and its amount varies nearly as the surface of the plate exposed to wind action.

The relation between the pressure as obtained from a plate and the standard pressure can only be ascertained by experiments, and different experimenters have assigned different values to it. Dr. Hutton makes the ratio 1·4, others have made it as high as 2, but it is now considered to be 1·8.

The instrument used for measuring the velocity of the wind is the revolving cup instrument known as Robinson's anemometer. It is considered that a constant ratio exists between the velocity of the wind and that of the cups actuated by the wind. That ratio was supposed to be 3, but recent carefully conducted experiments by Dr. Robinson place it at 2·28. More recent experiments indicate 2·4 as the ratio. As a general average result, it is considered that wind with a velocity of 20 miles per hour produces a standard pressure of 1 lb., or 1·8 lbs. per foot pressure on a flat board, and that the pressure increases as the square of the velocity.

The diagram, produced by the cup anemometer, as the apparatus is now arranged, does not enable the velocity in short periods of time to be ascertained with certainty; hence it is not possible to determine by its means the velocity in gusts of wind.

Osler's anemometer appears to afford the most direct and reliable means of ascertaining wind pressure on a flat surface.

The highest record arrived at by this instrument was a pressure of 90 lbs., which occurred on the 9th of March 1871 at Bidstone. It is stated that the instrument was graduated only up to 40 lbs., but the marker was driven on beyond to a distance estimated to represent about 90 lbs. Excepting this one result, the greatest pressure actually recorded is 50 lbs., which occurred in Calcutta; but there are numerous examples of pressures of 40 lbs., and between 40 and 50 lbs.

Professor Stokes states that the position of the anemometer may materially affect the velocity and pressures recorded by it. It may be so placed as to have partial shelter, in which case the recorded result is too small, or it may be placed in the draft passing round some obstruction to windward of it, in which case the record is too high.

Pressures deduced from wind velocities require to be received with great caution, firstly, because there is a doubt as to the accuracy of the estimated wind velocity; secondly, because there is a further doubt as to the relation between velocity and pressure; and thirdly, because the pressure is supposed to vary as the square of the velocity, so that any error in the estimated velocity becomes greatly exaggerated when turned into pressure.

Some instances of railway carriages being upset by wind are clearly established in France, India, and America, and one occurred in this country on the Chester and Holyhead line in 1868.

The pressure required to overturn railway carriages may be taken to vary between 28 and 40 lbs. per square foot.

A distinction is made between the pressures of gusts of wind, and those extraordinary destructive effects which arise from cyclonic action or tornadoes, one of which is cited as having occurred at Walmer causing great destruction as it passed along over a width varying from 450 to 700 feet, but it is not known whether the pressure was equal throughout the width at the same instant of time.

Another cyclone of somewhat similar character occurred in the Isle of Wight in November, 1877.

The movement of the recording paper as generally used with Osler's anemometer, is so slow that wind gusts have the appearance of being absolutely momentary in their action, but by causing the paper to travel quicker and by other observations, the duration of wind gusts is found sometimes to exceed half a minute, though they are generally of less duration.

As against the evidence which tends to show high wind pressures there are many facts recorded in Mr. Baker's evidence of structures of various kinds continuing to stand though unable to bear high pressures. Smallness of height or partial shelter may account for such cases, but as regards engineering structures placed high above the ground or otherwise in exposed positions, there appears absolute necessity to provide for large wind pressures.

Special provision for wind not always required.

VII. In the great majority of railway structures, namely, those made in brickwork and masonry, as well as iron bridges of moderate height and span, special provision is not required for wind pressure, because the weight and lateral strength imparted to such structures, in providing for the strains due to dead weight and load, is more than sufficient to meet any lateral wind pressures which can arise. Also, in girders up to considerable spans, the lateral stiffness given to them to resist the tendency to oscillation produced by moving loads at high speeds is generally sufficient to meet the requirements of wind pressures; and the evidence of Sir Thomas Bouch implies that, having provided amply for dead weight and moving loads in the Tay Bridge, he did not consider it necessary to make special provision against wind pressure.

Calculations of strength.

VIII. The report of Dr. Pole and Mr. Stewart, who were engaged in this inquiry for Sir T. Bouch, after referring to the knowledge possessed at the time of designing these piers, states as follows: "For these reasons, in designing the bridge, a maximum "wind pressure was assumed acting over the surface of a span and pier equal to "about 20 lbs. per square foot (being more than double what Smeaton allowed for "a very high wind), and the dimensions were calculated for this pressure, with the "usual margin of safety." It appears Dr. Pole and Mr. Stewart were wrongly informed on this subject, as Sir T. Bouch stated that he did not make any special provision for wind pressure.

The calculations of the action of wind pressure on open-work girders necessarily involve some assumptions. In those made by Dr. Pole and Mr. Stewart, and also by Mr. Law (who was employed by the Court), it is assumed that the pressures per unit of surface acting upon the leeward girder, so far as it is exposed to the wind, were one-half those acting on the windward girder. And on this assumption Dr. Pole and Mr. Stewart calculate that, with a wind pressure of 20 lbs., the stress on the minimum section of the wind ties running east and west at the lowest division of the pier would be,

with no train on the bridge - - - - 5·21 tons per inch
with light passenger train over one pier - - - 6·79 ,, ,,

It is to be observed that in making this calculation Messrs. Pole and Stewart have not considered the ties as performing the whole duty of resisting the wind, but they have deducted from 20 to 25 per cent. of the total force, which they consider to be the resistance the columns would offer to an amount of bending corresponding to the lateral motion assumed. The resistance to bending is, without doubt, an element contributing to the strength, so far as it can be relied upon; but having regard to the fact that these piers were composed of seven tiers of columns connected together by bolts and nuts, and that the base plates to which they were fastened at the top of the masonry were only held down at their bases by bolts passing through two courses of stone, we think that a reduction of 20 or 25 per cent. on account of the resistance of such columns to bending is not admissible, and that, as a matter of ordinary precaution, the calculation ought not to be so treated. But as this great reduction has been made in the strength of the ties, no further deduction in the usual margin of safety (or the factor of 4) should on any account be permitted.

The minimum sectional area of the ties is stated in that report to be 1·69 inches, and the total stress on the ties would therefore be,

with no train - - - - $5·21 \times 1·69 = 8·80$ tons
with train over pier - - - - $6·79 \times 1·69 = 11·47$,,

If these stresses be multiplied by 4, the usual factor of safety, the ultimate strength required in the ties would, under the assumed conditions, be,

with no train - - - - - $8·80 \times 4 = 35·2$ tons
with train over pier - - - - $11·47 \times 4 = 45·88$,,.

The ultimate strength given to these ties should not, therefore, have been less than 45·88 tons under the conditions assumed. But the mean ultimate strength of six of the ties tested by Mr. Kirkaldy without the lugs was only 25·6 tons, and the mean strength of 14 tie bars tested with the lugs was 24·1 tons, of which six broke with less than 22 tons, four of the latter giving way at unsound lugs, and two of them breaking with less than 21 tons.

The experiments were made on ties and lugs taken from the ruins, but no injury was apparent on them from that cause, and we think the weakness found in them was due to causes to which we shall now refer.

Cross-bracing.

IX. The tensile strength of the wrought iron used in the ties was proved by Mr. Kirkaldy's experiments to be 20 tons to the inch, and, the minimum sectional area

of the tie bars as measured being 1·625 inches, they ought to have carried 32·5 tons; but the bearing surface of the pin was much less than the minimum sectional area, and, the pin being placed very near the extremity of the bar, it was not capable of developing the whole strength of the metal, which yielded by tearing or fracture at the pin-hole.

Again, as regards the cast-iron lugs, the tensile strength of the metal obtained from the average of 14 specimens cut out of broken cast-iron columns was 9·1 tons per square inch, the weakest being 8·1 ton per square inch. Fourteen cast-iron lugs, to which the tie bars were attached, and which form portions of the diagonal cross-bracing between the columns, were tested in London. These tests were made by strains applied in the same direction as the lugs would be subjected to on the piers. Of these, 10 were found to be sound castings, and four unsound. Of the sound castings, the strongest bore less than three tons per square inch before breaking; the average 2·8 tons per square inch, and the weakest 2·44 tons per square inch before they broke.

We believe this great apparent reduction of strength in the cast iron is attributable to the nature of the fastenings, which caused the stress to be brought on the edges or outer sides of the lugs instead of acting fairly upon them. And we wish to direct attention specially to these results, because the employment of wrought-iron ties bolted to cast-iron lugs is a mode of construction frequently employed in other structures, and the deficiency of strength arising from it is not, we think, generally known.

As a question of ultimate strength, it may be urged that, if the weakest ties bore nearly 21 tons, the viaduct ought to have been able to resist 35 lbs. per square foot of wind pressure, because, according to the calculations of Messrs. Pole and Stewart, 35 lbs. of pressure would have been required to produce that strain. But Messrs. Pole and Stewart's calculation is based on the assumption that the columns and their connecting bolts bear 20 or 25 per cent. of the wind pressure, leaving only 75 or 80 per cent. to be carried by the ties; it also assumes that all the ties ar equally tightened up, that the columns are in their correct positions, and tha every part or member of the pier is performing its exact proportion of duty.

These are conditions which can only exist within the elastic limit of the materials, and the elastic limit of iron in tension is somewhere about half its ultimate strength; that limit once passed, it is impossible to say what would be the relation between the strains in the different members of which the pier was composed.

Mr. Kirkaldy's experiments show that the stretching or elongation of the ties, wh tested with their fastenings, was greatly in excess of that due to the elastic action of that material; a result attributable to the small bearing surfaces of the pins, gibs, and cotters, and to the conical holes in the lugs.

In considering the construction of these piers, it is further to be observed that ary considerable stretching of the diagonal bracing, and consequent departure of the columns from the vertical, was a derangement or distortion, which it was especially important to avoid, because such a movement could not take place without causing an unequal bearing at the bases or at the joints of the columns where it occurred, and might either result in fracture of the flanges or of the connecting bolts.

And if, from this or any other cause, one of the outer columns became fractured so as to be incapable of bearing weight, the L-shaped box girder would have been deprived of the support necessary to sustain the main girder resting upon it. The liability to accident from this cause is a direct consequence of the peculiar construction adopted in these piers.

The hexagonal form given to the pier had also the effect of throwing the main duty of resisting wind pressure upon the cross bracing between the inner 15-inch columns. The cross bracing on the four oblique planes formed between the 18-inch and 15-inch columns, and placed on those planes at an unfavourable vertical angle, contributed proportionately much less resistance to lateral pressure.

Before leaving the subject of the cross bracing, we think it right to point out that this part of the structure forms a comparatively small item in the quantity of metal and consequent cost of the bridge. The weight of the cross bracing in one of the high piers was stated approximately at 5 tons, the total weight of iron in the piers being 78 tons, and it will be seen by the return of the quantities of iron work used by the contractors, that out of a total quantity of iron of 10,518 tons, only 413 tons is classed under the head of bracing.

It would appear, therefore, that a great increase of strength might have been given to the cross bracing on which so much depends in resisting wind pressure without adding a large percentage to the cost of the bridge.

The wind force required to overturn the piers as a whole, assuming that there were no holding-down bolts, is estimated by—

	With no Train.	With a Train on Bridge.
	lbs. per square foot.	lbs. per square foot.
Mr. Law	36·38	34·33
Messrs. Pole and Stewart	37·4	$34\frac{1}{3}$

In these estimates it is, of course, assumed that the cross bracing and other parts are of adequate strength.

The holding-down bolts passed through two courses of stone; and if the effect of the additional weight thus brought into operation be taken into account, together with a fair allowance for the tenacity of the cement, the stability as against overturning would have been sufficient to resist 40 lbs. of wind, if the cross bracing had been made strong enough to resist that pressure.

An opinion has been frequently expressed that the bases of the piers were too narrow, and it is clear that the requisite stability could have been obtained more readily if the bridge had been made for a donble instead of a single line of railway; but with iron-work and bracing of sufficient strength in all their parts, held down by strong bolts bedded deep in the solid mass of the piers, there is no doubt that the caissons are wide enough, to permit of piers being constructed adequate to perform all the duty required.

Fall of the Bridge.

X. There is no absolute knowledge of the mode in which the structure broke down; the evidence of persons who happened to be looking at the bridge at the time agrees in describing lights falling into the river, and that these appearances lasted only a few seconds, but the evidence is not sufficiently clear and definite to determine by it which portion of the bridge fell first.

It is observable in the ruins of the bridge that the columns have for the most part separated where they had been bolted to the base pieces; in two piers the separation has taken place higher up the pier, one being at the first and the other at the second tier of columns.

At piers Nos. 33 and 37, which were at the disconnected ends of the girders, the masonry is considerably disturbed, and the stonework has been partly torn up where it was fastened to the base pieces by the holding-down bolts; this effect is especially observable on the windward sides of these piers. The fracture of the cross bracing are in almost every instance at the lugs.

Force of the storm.

XI. The storm which occurred at Dundee on the night of the 28th December, was recorded on board the "Mars" training ship, lying near Newport, as being of the force of 10 to 11 of the Beaufort scale, and was especially characterised by strong gusts at intervals. The evidences of wind force in the town of Dundee were not, however, such as to point to extreme wind pressure, but from the configuration of the land the main force of the gusts would probably take the line of the river.

Indications of weakness.

XII. The first indication of weakness in the bridge itself was the loosening of a number of the ties of the cross bracing, a fact observed by the inspector, Henry Noble, in October, 1878. He did not communicate this fact to Sir T. Bouch, but procured iron and packed the gibs and cotters, using for this purpose more than 100 iron packings about $\frac{1}{4}$ or $\frac{3}{8}$ of an inch thick in different parts of the bridge.

All the evidence relative to the condition of the ties states that they were, to all appearance, in proper order at the date of the inspection by General Hutchinson, on the 25th, 26th and 27th of February, 1878. The loosening which subsequently ensued must have resulted from lateral action, and was most probably due, as Sir T. Bouch suggested, to strains on the cross-bracing produced by storms of wind.

Sir Thomas Bouch considers that the loosening arose from the bending of the pins in the holes which had been left conical in casting the lugs, and it was, we think, one of the causes; but the small bearing surfaces between the gibs and cotters, and the tie bars, only about ·375 of a square inch, would tend to increase this effect, and it might have been further increased by displacement or movement at the ends of those struts where the fitting was imperfect.

Again, in October 1879 four of the columns were ascertained by Mr. Noble to be cracked with vertical cracks, two of them being in the northern part of the bridge still standing, and one in pier No. 38 under the high girders. The inspector (Noble) bound these columns round with wrought-iron bands, and communicated this fact to Sir Thomas Bouch, who came to the work, and, in reference to other indications of straining pointed out by the inspector, decided to have extra bracings made

for the curved part of the bridge north of the large girders. It has been already mentioned that the columns of the whole bridge were filled after their erection with Portland cement concrete, put in from the top, and concrete of this material, unless carefully managed, is liable to swell in setting; from this circumstance, and from the unequal contraction of cast iron and concrete by cold, internal strains might have arisen sufficient to produce such cracks. Cracks of a like character have occurred in other viaducts; and when the fracture is vertical it is capable of remedy, to a considerable extent, by hooping with wrought-iron bands.

In this state of the columns and ties the storm of the 28th December 1879 occurred, which would necessarily produce great tension on the ties, varying as the heavy gusts bore upon different parts of the bridge; and when under these strains the train came on the viaduct bringing a larger surface of wind pressure to bear, as well as increased weight on the piers, and accompanied by the jarring action due to its motion along the rails, the final catastrophe occurred.

The distance at which the girders were found from the piers, and the position of the wreckage on the piers, is such as would result from a fracture and separation taking place in the piers somewhere above the base of the columns; and such a fracture might have arisen from two causes: firstly, by the yielding of the cross bracing, and the consequent distortion of the form of the piers, which would throw unequal strains on the flanges and connecting bolts; or, secondly, fracture might have taken place in one of the outer leeward columns from causes similar to those which produced the fractures found in other columns shortly before the accident.

Opinions as the cause of the accident.

XIII. Sir T. Bouch states it to be his opinion that the accident was occasioned by the overturning of the second-class carriage and the van behind it by the force of the wind, that they were canted over against the girder, and that the force of the blow given by these vehicles at the speed at which they were travelling was sufficient to destroy portions of the girders, and so occasioned the fall. But in this opinion we do not concur, and do not consider that it is supported by the evidence of the Engineers who were called on the part of the Railway Company, Sir T. Bouch, and the Contractors,

Dr. Pole, Mr. Stewart, and Mr. Baker, all of whom were called on behalf of Sir T. Bouch, although they suggest the possibility of some shock acting in addition to the wind pressure, all concur in attributing the first failure to the lugs of the cross-bracing. Mr. Cochrane believes that if the columns had been strongly braced, strongly fitted, and strongly held down by holding-down bolts the pier would have been standing now, and adds, " it is a question of cross-bracing, of course." Mr. Law also considers that the structure yielded because the ties were inadequate.

Conclusions arrived at by the Court.

Such being the nature of the case brought under our consideration in this inquiry, we have to state as our opinion,

1st. That there is nothing to indicate any movement or settlement as having taken place in the foundations of the piers which fell.

2nd. That the wrought iron employed was of fair strength, though not of high quality as regards toughness.

3rd. That the cast iron was also fairly good in strength, but sluggish when melted and presented difficulty in obtaining sound castings.

4th. That the girders which have fallen were of sufficient strength, and had been carefully studied in proportioning the several parts to the duty they had to perform; in these girders some imperfections of workmanship were found, but they were not of a character which contributed to the accident, and the fractures found in these girders were, we think, all caused by the fall from the tops of the piers.

5th. That the iron piers used in place of the brick piers originally contemplated were strong enough for supporting the vertical weight, but were not of a sufficiently substantial character to sustain, at so great a height, girders of such magnitude as those which fell. That the cross bracing and its fastenings were too weak to resist the lateral action of heavy gales of wind.

6th. That the workmanship and fitting of the several parts comprising the piers were inferior in many respects.

7th. That although a large staff of assistants and inspectors was employed, we consider that a sufficiently strict supervision was not exercised during the construction of that part of the work made at the Wormit foundry. We think that the great inequality of thickness in some of the columns, the conical holes cast in the lugs, and several imperfections of workmanship which have been ascertained by this inquiry, ought to have been prevented.

8th. That the arrangements for the supervision of the bridge after its completion were not satisfactory, inasmuch as it was intrusted solely to Henry Noble, who, although an intelligent man and very competent in the class of work to which he had been accustomed, possessed no experience in structures of iron work, nor does it appear that he received any definite instruction to report as to the state of the iron work of the bridge.

9th. That Henry Noble having become aware that many of the ties of the cross bracing were loosened in October 1878, ought at once to have informed Sir T. Bouch of this circumstance. Had he done so, there would have been ample time to have put in stronger ties and fastenings before the occurrence of the storm which overthrew the bridge.

10th. That the ties of the cross bracing had been tightened up and brought to their bearing, before the date of the inspection by General Hutchinson, and the fact that many of them became loose so soon afterwards, was an evidence of weakness in this part of the structure, and of a departure from the proper inclination or batter of the columns where it occurred; and we think that the loosening of the ties to an extent sufficient to permit the insertion of pieces of iron $\frac{1}{4}$ or $\frac{3}{8}$ of an inch thick indicated a considerable change of form of the pier, and rendered it doubtful if the piers could have recovered their form when the wind action ceased. The employment of packing pieces under such circumstances might have had the effect of fixing the parts of the structure where they were applied in their distorted form.

11th. That notwithstanding the recommendation of General Hutchinson that the speed of the trains on the bridge should be restricted to 25 miles per hour, the railway company did not enforce that recommendation, and much higher speeds were frequently run on portions of the bridge.

12th. That the fall of the bridge was occasioned by the insufficiency of the cross bracings and its fastenings to sustain the force of the gale on the night of December 28th, 1879, and that the bridge had been previously strained by other gales.

13th. That although the general bearing of the evidence indicates the cross bracing as being the first part to yield, yet it is possible that the fall of the bridge may have been occasioned by a fracture, or partial fracture, in one of the outward leeward columns, produced by causes analogous to those which fractured other columns shortly before the accident; for if a fracture, or partial fracture, of a dangerous character occurred in one of these columns, the extra strain brought on by the force of the gale, accompanied by the weight and tremor of the train, might have led to its final rupture.

14th. That the first or southern set of continuous girders, covering five spans, was the first that fell after the engine and part of the train had passed over the fourth pier, and that the two consecutive sets of continuous girders, each covering four spans, were in succession pulled off the piers on which their northern ends rested, by the action of the first set of continuous girders falling over, and probably breaking some of the supporting columns.

15th. That the extent of the work which fell must be attributed to the employment of long continuous girders, supported by piers built up of a series of cast-iron columns of the dimensions used.

Recommendations.

In conclusion we have to state that there is no requirement issued by the Board of Trade respecting wind pressure, and there does not appear to be any understood rule in the engineering profession regarding wind pressure in railway structures; and we therefore recommend that the Board of Trade should take such steps as may be necessary for the establishment of rules for that purpose.

We also recommend, before any steps are taken for the reconstruction of the Tay Bridge, that a careful examination should be made of those parts of the structure left standing, especially as regards the piers, with a view to ensuring such alterations and amendments as may be necessary to give to these portions of the work complete stability. And we transmit herewith a further report from Mr. Law on that subject.

We have the honour to be,

Sir,

Your most obedient Servants,

W. YOLLAND,
W. H. BARLOW.

REPORT OF MR. ROTHERY.

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REPORT.

TO THE RIGHT HONORABLE THE PRESIDENT OF THE BOARD OF TRADE.

SIR, London, 30th June, 1880.

Preliminary Remarks.

(1.) FOR reasons, into which it is not necessary to enter, I have thought it better to send in my own separate Report, instead of joining in a Report with my colleagues.

(2.) The two Reports will be found to agree substantially in their conclusions. A statement of the points, on which we agree, and on which we do not agree, will be found at the end of this Report.

(3.) Although this Report is only signed by myself, I have retained the plural number throughout, as it would require some time to make the necessary corrections, and no misconception is likely to arise therefrom.

Course of the Inquiry.

(4.) HAVING been directed by an order dated the 31st December last, to hold a formal investigation, under the provisions of the "Regulation of Railways Act, 1871," "into the causes of and the circumstances attending an accident, which took place "on the railway bridge crossing the Firth of Tay, on the North British Railway on "the twenty-eighth" of that month, we deemed it expedient to proceed at once to Dundee, for the purpose of making a personal inspection of the bridge, and at the same time of examining, whilst the facts were still fresh in their memories, any witnesses, who might be able to speak to the occurrences.

First examinations at Dundee.

(5.) Accordingly, on the 3rd day of January last the Inquiry was opened in the Assize Court at Dundee, which had been kindly placed at our disposal, Mr. Trayner appearing for the Board of Trade, and Mr. Balfour for the North British Railway Company. On that day, and on the following Monday and Tuesday, a number of witnesses were examined, chiefly in regard to the "circumstances attending" the casualty; when finding that there were no more witnesses, whom the parties were then in a position to call before us, we adjourned the further hearing to allow time to collect full information as to the past and present condition of the structure, without which it seemed to us impossible to prosecute our inquiry into the "causes," which had contributed to the accident.

Steps taken to get information.

(6.) With a view to obtain this information, we appointed Mr. Henry Law, a member of the Institution of Civil Engineers, with directions to make a careful inspection of the whole of the structure, and to report to us fully thereon, and as to the probable causes of the casualty. We also directed him to select specimens of the wrought and cast iron, and to forward them to Mr. Kirkaldy for the purpose of being tested at his establishment at Southwark. We also called upon the railway company to furnish us with detailed information of the weight, strength, and dimensions of different parts of the structure, of the forces which would be required to overthrow it, and of the causes to which, in their opinion, the fall of the bridge was due. Photographs also were ordered to be taken of the fallen piers and girders, as well as of the remains of the engine and carriages, when they should have been recovered from the bottom of the river.

Second examinations at Dundee.

(7.) Whilst waiting for this information, we were told that there were a number of witnesses at or near Dundee, who could give very important evidence as to the con-

dition of the bridge before the accident. We therefore returned to Dundee, and from the 26th of February to the 3rd of March last, we were engaged examining a number of witnesses, chiefly with reference to certain alleged defects in the materials and workmanship of the bridge, and to the speed at which trains were accustomed to cross it, Mr. Trayner and Mr. Balfour appearing as before.

Examinations at Westminster.

(8.) The information, for which we had been waiting, having been at length obtained, the inquiry was resumed at Westminster, and continued from the 19th of April until the 8th of May, Mr. Trayner and Mr. Balfour representing the Board of Trade and Railway Company respectively, Mr. Bidder appearing for Sir Thomas Bouch, the Engineer, and Messrs. Webster and Macrory for the Contractors, Messrs. Hopkins, Gilkes, & Co. On this occasion a very large amount of evidence was taken, chiefly of a technical and scientific character, with the object of ascertaining the causes which had contributed to the fall of the bridge.

Close of the inquiry.

(9.) Finally all the witnesses having been examined, and counsel heard for their respective parties, the Inquiry was declared to be closed; and it now only remains for us to state the conclusions, to which we have come, after a most careful and anxious consideration of the facts contained in the evidence and documents, which have been laid before us. A copy of this evidence, and of the more important documents will be found annexed to this Report, and to these we must beg to refer. The circumstances of the case are as follow.

History of the Undertaking.

Original design.

(10.) It seems that, a proposal having been made to build a bridge across the Firth of Tay opposite to Dundee, Sir Thomas Bouch caused borings to be made, from which he was led to believe that hard rock would be found extending across from side to side, at no great depth below the bed of the river. He accordingly designed a bridge, which was to consist of open lattice girder-work, and which was to be carried across the river on piers mainly consisting of brick, built up from the solid rock as a foundation. The scheme having been approved, a contract was on the 8th of May 1871 entered into with Messrs. De Bergue & Co. to undertake the work. After the first 14 piers on the south side had been built, and carried up to a height of 20 feet above high-water level, it was found, on sinking the cylinders for the 15th and 16th piers, that what had been taken by the borers for solid rock, was only a bed of hard conglomerate about 3 or 4 feet thick, on piercing which they came into soft mud or sand of unknown depth, the rock having disappeared. The discovery seems to have been made about May, 1873, for we have a report to Sir Thomas Bouch from Mr. Paterson, the resident engineer, dated the 29th of that month, in which the fact is first mentioned.

Alteration of plans.

(11.) The result of course was that the design had to be altered, and to meet the difficulty, which had arisen, Sir Thomas Bouch proposed that the area of the foundations should be considerably increased, and that light columns of iron should be substituted for the brick piers previously intended; and there is a report from Sir Thomas Bouch to the directors, dated the 11th December 1873, in which he explains at length the advantages of the proposed changes.

Change of contractors.

(12.) In the meantime Mr. Charles de Bergue, the leading partner in the contractor's firm, had become so ill as to be unable to attend to business, and it became necessary to transfer the contract to other hands. This was accordingly done, and on the 26th of June 1874, a contract was entered into with Messrs. Hopkins, Gilkes, & Co., of Middlesborough, to complete the work, the new contractors agreeing to take over from Messrs. de Bergue the whole of the existing staff and plant, as well as the foundry works, which had been erected at Wormit, near the southern end of the bridge, and where it was proposed to cast some portions of the ironwork required in the construction.

Final designs.

(13.) The proposal to alter the piers from brick to iron seems to have been made before the contract was signed with Messrs. Hopkins, Gilkes, & Co., but the final designs were not settled until afterwards; for Sir Thomas Bouch told us that they were settled in consultation with Mr. Gilkes at Middlesborough; and there is a letter from Mr. Gilkes to Sir Thomas Bouch dated the 9th of June 1875, in which he

speaks of the proposed "enlargement of the spans and certain alterations of the piers," which he states had, after "long and careful consideration," been at length decided on. The "enlargement" here referred to is that of the large spans crossing the navigable part of the river, which as originally designed were to have a width of 215 feet from centre to centre, and 200 feet between the piers, but in the final plans they were to be 245 feet from centre to centre, except two, which were to be 227 feet each.

(14.) From this time the work progressed with great rapidity, a large number of men being constantly employed both on the bridge itself and at the Wormit foundry; and although some delay occurred from the fall, during a heavy gale of wind, of two of the large iron girders, whilst they were being raised into their positions, together with the piers on which it was proposed to place them, the bridge was completed, if not within, at all events very soon after, the stipulated time. *Completion of the work.*

(15.) On the completion of the bridge the usual notices were sent to the Board of Trade, and thereupon General Hutchinson was directed to go down and inspect it. His inspection took place on the 25th, 26th, and 27th February 1878, and on the 5th of March following he reported that he saw "no reason why the Board of Trade "should object" to the bridge being used for passenger traffic; he stated, however, that it would "not be desirable that trains should "run over the bridge at a high "rate of speed," and suggested "25 miles an hour as a limit, which should not be "exceeded," adding that "very careful attention will be required to ascertain from "time to time that no scouring action is taking place in the foundations," and that he should wish, if possible, to have an opportunity of "observing the effects of "a high wind when a train of carriages is running over the bridge." *Inspection by Board of Trade officers.*

(16.) Some delay occurred, owing to the approaches not being finished, but at length in June 1878 the bridge was opened for passenger traffic, and from that time trains continued to run regularly across it until the evening of the 28th of December last, when the accident, which we are now about to describe, occurred. *Opening of bridge.*

Account of the Accident.

(17.) On the evening in question the train from Edinburgh arrived in due course at St. Fort Station, which is the last before crossing the bridge, and there the tickets of all the passengers for Dundee were, as usual, collected. We are told that there were in the train at that time, 57 passengers for Dundee, 5 or 6 for Broughty Ferry, 5 for Newport, 2 season ticket holders, the engine driver, stoker, and guard of the train, and 2 other guards, making 74 or 75 persons in all. The tickets having been collected, the train proceeded on its course, leaving the St. Fort Station at 7.8 p.m., and on approaching the cabin, which stands at the southern end of the bridge, the speed was slackened to enable the engine driver to take the baton, without which he is not allowed to cross the bridge. On receiving it, steam was again got up, and the train passed on to the bridge; upon which the signalman, Thomas Barclay, signalled the fact to the north cabin, and made an entry in his book of the time, which he told us was 13 minutes after 7 o'clock. At this time it was blowing a strong gale from about W.S.W., almost directly across the bridge; the night was also extremely dark, for although there was a full moon, heavy clouds obscured its face. *Passage of the train.*

(18.) It seems that a person named John Watt, a surface man in the employment of the North British Railway Company, had gone to keep Barclay company, and was in the cabin when the train passed, and it is from him that we have the best account of what then occurred. Whilst Barclay was attending to his duties, entering the time in his book and making up the stove fire, Watt was watching the train from the window in the cabin door, which looks northward down the line. According to him, when the train had got about 200 yards from the cabin, he observed sparks flying from the wheels; and after they had continued for about three minutes, there was a sudden bright flash of light, and in an instant there was total darkness, the tail lamps of the train, the sparks, and flash of light all disappearing at the same instant. On informing Barclay of what had occurred, the two men endeavoured at first to make their way along the bridge, but finding it impossible to do so, owing to the violence of the wind which was then blowing, they got down to the side of the river, and after a time were able to make out that a large portion of the bridge had been carried away. On further inquiry it was ascertained that the train had also fallen into the river, and that every person in it had perished. *Fall of the bridge.*

Description of the Bridge.

(19.) In order to understand what had really occurred, it will be necessary that we should now give a general description of the nature and character of the structure.

Form of the bridge.

(20.) As finally constructed, the bridge, which had a total length from cabin to cabin of 1 mile 1,705 yards, was carried across the river on 85 piers, of which the first 14, counting from the south shore, were entirely of brick, the rest being for the most part composed of iron columns. Starting from an abutment on the south shore, it curved to the left for the first three spans, which brought it at right angles to the course of the river, which here runs nearly due east and west; it was then straight to pier 53, whence it curved sharply to the right with a radius of 20 to 22 chains, until it reached the north shore. For the first three spans after leaving the south shore the roadway slightly fell; it was then level to pier 6, whence it rose with a gentle incline of 1 in 353 to pier 29; from 29 to 30 the incline was 1 in 490; it was then level for six spans, and at pier 36 it began to fall, the incline from 36 to 37 being 1 in 130, after which the fall was extremely rapid, being about 1 in 74, until it reached the north shore. It will thus be seen that from soon after leaving the south shore there was a gentle rise till they reached pier 30, where the under side of the bridge was about 88 feet above high-water mark; from there the bridge was level for six spans; and from pier 37 the fall was very rapid to the north shore.

Provision for expansion and contraction of iron.

(21.) To allow for the expansion and contraction of the iron, the girders, of which the bridge was composed, were not continuous throughout their entire length, but were divided into sections of four, five, or six spans; and whilst the spans of each section were firmly riveted together, so as to form one continuous girder, the sections were quite distinct and separate. Each section was rigidly attached to the top of one of the piers, by which it was supported, whilst on the other piers it rested on rollers having bevelled flanges. Where the section is rigidly attached to the pier, it is called a fixed bearing; where the ends of two sections meet, it is called an expansion joint; the others being called roller bearings.

The high girders.

(22.) Between piers 28 to 41, where it crossed the navigable part of the river, the girders were raised so as to give additional headway to passing vessels, the lower booms of this portion being in a line with the upper booms of the portions north and south of it. The consequence was that, whilst from the south shore to pier 28, and again from pier 41 to the north shore, the roadway was carried on the upper booms, and therefore outside and on the top of the girders; between piers 28 and 41 it was carried on the lower booms, and therefore inside and on the bottom of the girders. These latter were called the high girders; and as they were entirely carried away, it is to this part of the structure that our attention must be more particularly directed.

The High Girders.

Their length and divisions.

(23.) The high girders consisted of 13 spans, of which 11 were 245 feet and two 227 feet each, making a total of 3,149 feet, or very nearly 1,050 yards. They were divided into three sections; the first, beginning from the south, containing five spans of 245 feet each; the second, four spans, two of 245, and two of 227 feet each; and the third, four spans each of 245 feet. There were fixed bearings at piers 31, 35, and 39, expansion joints over piers 33 and 37 and at the two extremities, and the rest were roller bearings.

Form and construction of girders.

(24.) The girders, which were of wrought iron, were 27 feet high, the sides being 14 feet 10 inches apart from centre to centre. The upper and lower booms on each side were trough-shaped, 2 feet wide, and 15 or 16 inches deep, and were connected together by flat tensile bars in pairs riveted to each side of the booms, as well as by I-shaped struts placed between the sides of the booms, and secured to them and to the tensile bars at their intersections. The two upper booms were braced together by wrought-iron beams with diagonal stays; but the lower booms, which in this part carried the permanent way, were connected by transverse wrought-iron, fish-shaped girders, set about 5 feet 5 inches apart, and firmly riveted to the upper side of the booms. The girder over each span was complete within itself, the vertical ends being of similar construction to the booms, and 18 inches wide on the face. On the whole, the girders appear to have been well constructed, and to have been carefully proportioned to

the strains, which they had to bear; and as there is no reason to suppose that the casualty was due to any defects therein, it is not necessary to describe them more in detail.

The supports. (25.) With the supports, however, it is otherwise, for the columns on which the girders rested, have all, from 29 to 40 inclusive, given way, and in every case but two from their very bases; and it therefore becomes important to examine their construction with some care.

The foundations. (26.) We have said that it was originally intended to build the piers, which supported this part of the structure, of brick; but that, when it was found that the rock had disappeared, it was determined to lighten the piers by making them of cast-iron columns, and at the same time to increase considerably the area of the foundations. To obtain foundations for the piers, wrought-iron caissons 31 feet in diameter were constructed on the shore, which, on being lined with 18 inches of brickwork were floated out, and sunk in their proper places. This was an extremely difficult operation, but appears to have been successfully performed. After a caisson had been sunk as low as was deemed necessary, the centre was filled up with concrete; and upon this was built a hexagonal-shaped pier, measuring 27 feet 6 inches from east to west, and 15 feet 6 inches from north to south; the lower part of which was faced with brick, whilst the four upper courses were faced with stone, the centre, as in the case of the caissons, being filled with concrete. And at the angles of the hexagonal pier were placed six cast-iron base pieces, 2 feet in height, and secured to the pier by holding-down bolts passing through the two upper courses of stone; and upon these were raised the columns. The arrangement of the foundations, the pier, and the base pieces will be best seen from the plan annexed to this Report, which is taken from a drawing in Mr. Law's report. *Vide plan annexed.*

The columns. (27.) The columns, of which there were six on each pier, were all of cast iron and hollow, the two outer being 18 inches, whilst the four inner ones were only 15 inches in diameter each. They were built up in tiers or sections, those on piers 28 and 41, where the higher and lower girders met, consisting of six tiers, whilst those on all the piers from 29 to 40 inclusive consisted of seven tiers. Each tier was attached to the adjoining tiers, as well as to the base pieces, by eight screwed bolts, $1\frac{1}{8}$ inches in diameter, passing through holes in flanges cast with and at either end of each section of columns. As to the thickness of the metal in the columns, which appears to have been altered during the progress of the work, we shall presently have a few words to say. The columns, after they were erected, were filled with concrete, not indeed with a view of adding to their strength, but to prevent internal corrosion.

The struts and ties. (28.) To prevent the columns from buckling or bending they were braced together at every joint by wrought-iron struts and ties. The struts, which were horizontal, consisted of two channel irons, placed back to back, which were secured at each end by $1\frac{1}{8}$-inch bolts passing through lugs on the columns.* The rectangular openings thus formed by the struts and columns were stayed diagonally by flat tie bars, $4\frac{1}{2}$ inches broad and half an inch thick. The upper ends of these tie bars were attached in the same way, as the struts, to lugs cast on the columns; whilst the lower ends were secured between two iron plates, $4\frac{1}{2}$ inches by $\frac{3}{8}$ths of an inch thick, called sling plates, by gibs and cotters,† the lower end of the sling plates being attached by bolts to lugs on the columns.

The spigots. (29.) At the end of each tier or section of the columns, except where they rested on the base pieces, was an inner projecting rim or spigot, about three-quarters of an inch deep, so as to allow each section to fit into the one below it; this also, we are told, was not done with a view to give any additional strength to the columns, but simply to prevent any sliding movement of one section over another.

The triangular grouping of the columns, and the L girders. (30.) There is another point in connexion with the columns, to which it is also important to call attention. The six columns, of which each pier consisted, were divided into two triangular groups, composed of one outer and the two next inner columns; and upon each group of three columns was placed a wrought-iron L-shaped girder, having its two ends resting on the inner columns, and its angle on the outer

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* By the term "lugs," which is the Scotch word for "ears," are here meant projecting pieces of iron, placed on the outside of the column, and in the angle between the flange and the shaft; they were cast with the columns, and had their bolt-holes ready made, as they issued from the mould.

† The gibs and cotters referred to consisted of wedge-shaped pieces of iron, passed through slits both in the sling plates and in the lower end of tie bar, and which, when driven home, served to tighten up the tie bar, and thus to bring the cross bracing to its bearings.

column. Owing, too, to the inclination, or as it is technically called the batter, of 12 inches given to each of the columns, that of the outer columns being towards the centre in a plane at right angles to the line of the bridge, that of each pair of inner columns towards each other in a plane in the line of the bridge, the tops of the columns in each triangular group were brought somewhat closer together than they were at their bases; whilst the two groups were as far apart from one another at their tops as they were at their bases. There was, moreover, no connexion between the two L girders, so that each of the piers on which the bridge was supported may be said to have consisted of two three-legged stools, having no connexion with one another, beyond the ties and struts, between the inner columns, of which we have spoken.

Longitudinal girders. (31.) To complete the description of the bridge, it should be stated that upon each of the L girders there was a wrought-iron cellular girder, running north and south in the line of the bridge; immediately above which were the longitudinal lattice girders, forming the sides of the bridge. And, as this cellular girder lay in a line, equidistant from the centres of the three columns forming each triangular group at their tops, it will be seen that the whole of the superincumbent weight was borne equally between the two outer and the four inner ones, each of the outer columns thus bearing double the weight of any one of the inner columns.

Rollers. (32.) Upon the upper side of the cellular girder above referred to was bolted a massive cast-iron plate, a similar plate being bolted to the under side of the longitudinal lattice girder of the bridge; and between these two plates were placed the cast-iron rollers referred to above, each 5 inches in diameter and 2 feet long, and with flanges of three quarters of an inch deep; except, of course, where there was a fixed bearing, when the longitudinal lattice girder was attached directly to the cellular girder by screwed bolts.

Condition after the Accident.

(33.) Let us now see what was the condition of the bridge immediately after the accident.

The Girders. (34.) And, first, as regards the girders. These, it seems, were lying in the bed of the river to the east of, and at some distance from the base of the piers, having turned over on their sides, so that what had been the east side was now the bottom, the west side forming the top. It appears from a plan, which was put in by the railway company, and which will be found in the Appendix, that the girder did not lie in a straight line, but that the three sections, of which it was composed, formed three distinct arcs, with their concave sides towards the piers, being nearest to the piers at the expansion joints, and furthest from them at the fixed bearings. Thus at piers 28, 33, 37, and 41, where there were expansion joints, the distances of the girder from the piers were respectively 22 feet 6 inches, 21 feet, 25 feet 6 inches, and 23 feet; whilst at piers 31, 35, and 39, where there were fixed bearings, the distances were respectively 42 feet 6 inches, 51 feet, and 44 feet 6 inches. At the intermediate roller bearings the distances were something between the two, the only exception being opposite to pier 29, where the distance from the pier was only 16 feet, a not unimportant fact to which we shall presently have occasion to allude.

The piers and columns. (35.) Secondly, as regards the piers. There was nothing to show that there had been any movement or settlement in any of the foundations; but the joints of the masonry of the hexagonal piers had in almost every case been severely shaken, and in two instances the two upper courses of stone on the west side had been wrenched off and tilted up on end. It was, however, to the columns that the greatest injury had been done. All these, from piers 29 to 40, had been entirely carried away, with the exception of the two lowest tiers on 29, and the lowest on 30. In almost every instance the bolts, which held the columns to their base pieces, as well as those, which attached the several tiers to one another, were broken, and the tiers lay some on the piers, but most of them in the bottom of the river to the eastward of the piers. In a great many instances the whole or portions of the flanges had been broken off, sometimes carrying with them part of the shaft. What however was chiefly to be remarked, was that the cast-iron lugs had almost all broken, whilst the wrought-iron struts and ties for the most part remained uninjured. This was especially noticeable

on the piers left standing at the two extremities, namely Piers 28 and 41; where the lugs on the sides, facing the fallen girders, were almost all broken, and the ties, which had held the two 15-inch columns together, were hanging loosely from their ends.

(36.) Thirdly, as regards the train. This consisted of the engine and tender, a third-class carriage, then a first-class, then two third-class, then a second-class, and lastly the guard's van. Of these the engine, the tender, and the four first carriages were found in the fifth or last span of the first section of the high girders, whilst the second-class carriage and the guard's van were in the fourth, but close to its junction with the fifth span. The engine and tender were on their sides, as well as the last carriage and the guard's van; but the four intermediate carriages were standing upright on their wheels, having, it is supposed, been floated after the accident by the air enclosed by the roofs. *The train.*

Causes assigned for the Casualty.

(37.) The next question to be considered was, to what causes the fall of the bridge was to be attributed.

(38.) And first it may be well to state what are the views entertained by those most deeply interested in the case, the company, the engineer, and the persons chiefly concerned in building the bridge. It seemed to us that these gentlemen had a right to have their views fully and clearly stated, and their arguments carefully weighed and considered, for none could know better than they the nature and character of the structure. *By the parties interested.*

(39.) We accordingly addressed a letter to the company, asking them to what causes they attributed the fall of the bridge; and in reply we were informed in a letter dated the 12th of March last that, "apart from the overpowering violence of the wind," they were "not yet aware of any circumstances which in themselves would account for the disaster." Up to this time, then, the company were under the impression that the fall of the bridge was due to the violence of the wind alone; and this was the conclusion, to which they had come, more than two months after the casualty had occurred, during which time they must have obtained full knowledge of all the facts, and have had ample opportunities of conferring with Sir Thomas Bouch, and the engineers and officers of the line. *Company's views.*

(40.) On the 22nd of April following Mr. Gröthe, the resident engineer and manager for the contractors during the whole of the operations, was examined, and on being asked what in his opinion had caused the fall of the bridge, he stated that in all probability, when the train was on span 32, the end of the girder at the expansion joint over pier 33 had been lifted off its bearings, and having been blown off the top of the pier, it had come down smashing the pier below it. Everything, he said, pointed to what he had "heard called a simple smash, something falling from the top, and in its fall crushing everything below it;" and that this would have happened, "no " matter what that pier had been made of, if it had been made of steel from top " to bottom." It is not very easy to follow Mr. Gröthe's reasoning; but what we understood him to say was, that the accident was not due to any want of strength in the piers or their fastenings, but to the end of the girder at the expansion joint having been blown off the top of the pier, and to its then coming down smashing everything below it. But it might be said in reply that, before this could have happened, the permanent way must have been fractured at that point, the permanent way being continuous, although the girders are disconnected at the expansion joints; and that there is nothing to show that the permanent way had been broken at any of the expansion joints. Moreover, if the bridge had fallen in the way he supposes, by the end of the girder being blown off the pier at the expansion joint, and coming down, smashing the pier below it, we should naturally expect to find it, if not on, at all events near the base of the piers; but, instead of this, it is at a considerable distance from the base of the piers, in one place no less than 51 feet from it. All, however, that we need say about Mr. Gröthe's theory is, that it seemed not to have found much favour with any of the witnesses who followed him, for none of them were prepared to support it. *Mr. Gröthe's opinion.*

Sir Thomas Bouch's opinion.

(41.) Mr. Gröthe, as I have said, gave his evidence on the 22nd April; and on the 30th of the same month we have a new theory set up. On that day Sir Thomas Bouch was examined, and in answer to a question put by Mr. Bidder, what in his opinion caused the fall of the bridge, Sir Thomas replied (Q. 16,798): "Well, I have thought a great deal about it very anxiously, and my own opinion is "fixed now; that it was caused by the capsizing of one of the last, or the two last "carriages, that is to say, the second-class carriage and the van; that they canted "over against the girder." Sir Thomas was subsequently asked by the court to explain more fully what he meant, and he then gave the following evidence:—

17,186. (*The Commissioner.*) You have told us that you think the cause of the accident was the train coming into collision with the girder, with these ties, I suppose?—Yes, I think it was caused by those two things,—coming into collision with the ties and heing capsized by the wind.

17,187. You do not mean that it came into collision with the boom; you mean that it came into collision with one of these ties?—Yes, I think so; with one of the girder ties.

17,189. Do you think that the mere breaking of any one of these ties of the girder would be sufficient to bring it down?—I do not know that the mere breaking of any one of them would be sufficient, but there are several struts and ties where this second-class carriage and the van were found, and I have had the whole thing surveyed and made into a plan.

17,192. Do you think that taking away two of these ties and struts there would be sufficient to briug the bridge down?—Most undouhtedly, with that wind.

17,193. Put the wind aside. Do you think that the breaking away of two of those ties and struts would be sufficient to bring the bridge down?—Yes.

17,194. By cutting them through? Do you think that that would be sufficient to bring the bridge down? —I do.

17,195. You think, therefore, that this bridge was so constructed that, if one or two of these ties gave way, the whole of the bridge between the high girders would come down?—I think so, that is to say, if you cut them.

17,196. So constructed that if one or the other of these ties gave way?—I do not know as to one, but certainly two.

17,197. If two of them came dowu, the whole length of the bridge between the high girders would come down?—Of course the girder coming down sends the pier down, and they all go one after the other like.

Dr. Pole's opinion.

(42.) Sir Thomas Bouch gave his evidence on the 30th April and the 3rd of May, and on the 5th an entirely new theory is started. On that day Dr. Pole, a gentleman of considerable scientific attainments, who has throughout these proceedings been Sir Thomas Bouch's confidential adviser, having been present and heard all the evidence given at Westminster, was examined, and on being asked by Mr. Bidder, "What would "you say was more probable as being the explicable cause of what happened to "the Tay Bridge?" he replied:—

18,607. As I cannot think that a statical force would have broken down the bridge,—any statical force that, as far as I know, could come upon it,—I think the rupture must have been caused by the superaddition to the statical force already existing of something like a shock of some kind. The bridge had been already strained considerably by the wind, as nobody denies; and if I am right in being unable to find any statical force that was sufficient to rupture it, I can only conclude that there must have been something super-added, and the most reasonable supposition to my mind is that that something should have been in the nature of a shock, and I am led in a great measure to think that this is rendered probable by the fact which struck me at the very first moment I looked at the bridge, and that is, that it is almost universally the cast iron that has gone, and not the wrought iron. I do not know the details, but the fact impressed itself very strongly upon my mind, that in all cases these ties have broken by a rupture of the cast iron and not by any fracture of the ties themselves; and since we know that cast iron gives way so much more readily under shocks than wrought iron, and will resist statical pressure very well, it occurred to me, as an explanation worthy of consideration, whether there might not have been a shock in addition to the statical strain which broke those lugs.

(43.) That the theory set up by Dr. Pole was really quite different from that started by Sir Thomas Bouch is clear from the answers, which he gave to the following questions, put to him by Mr. Bidder:—

18,746. My learned friend asked you your opinion as to whether the second-class carriage, if projected against the leeward girder would break two struts, and you said that you doubted whether it would break them altogether away; but in your observations as regards the impact of those carriages as a shock upon the bridge, you did not necessarily assume that the struts were destroyed, did you?—Oh, no. I rather based my idea of the shock on the expenditure of *vis viva* in a lateral direction on the eastern girders, and I did not attach much weight to the possibility of the train breaking down the girders. I do not think we have evidence that it was the girders that gave way. I would rather incline to the opinion that it was the pier that gave way. I do not think there is any evidence to show that the girder gave way first. Of course the destruction of two struts of the girder would cause it to give way; but I do not think there is evidence that that took place, and I based my opinion that the carriages in getting off the line might have caused the destruction of the bridge rather upon the expenditure of the *vis viva* in a lateral direction on the eastern girder by the forcible contact of the two carriages in that direction. That is sufficient in my mind to account for the destruction of the pier, and at the same time it does not involve the previous destruction of the girder.

18,747. (*Colonel Yolland.*) Transmitting the effect into the columns of the piers ?—Transmitting the effects into the columns of the piers. The *vis viva* must have been extinguished, and if a considerable portion of it was diverted against the eastward girder, I do not see how we can evade the conclusion that it must have acted upon the pier, in addition to and in the same direction as the strain already existing from the wind. That was the last straw (a very heavy straw), which may have caused, I think, the fracture of these ties. I do not go further than that.

18,748. Then, at any rate, I understand that in whatever way these causes operated, the effect of them, and the first absolutely fatal effect upon the bridge, was the breakage of one of the columns of the pier ?—The breakage of the tie. I do not think the columns would go first. I said, in answer to Mr. Trayner, that I considered this the weakest part of the structure (*pointing it out*), and I consider that this would be the first thing to go.

18,749. Do you think that the shock of a train on this part of the girder, which did not destroy the girder, would be capable of imparting such action to that lower tie as to destroy it ?—Yes, if it was transmitted against the eastward side, because it would certainly then be transmitted through the eastward girders, and to the piers upon which the girders rested.

18,750. (*Mr. Bidder.*) Any lateral pressure, or any lateral blow upon the girder, must ultimately, must it not, be transmitted absolutely undiminished to the lowest pier ?—Yes, it must be so; the amount of *vis viva* is so large.

(44.) Without accepting Mr. Bidder's somewhat doubtful theory that any lateral pressure, "or any lateral blow upon the girder, must ultimately be transmitted *absolutely undiminished* to the lowest pier," it is clear that, what Dr. Pole means, is, that the cast-iron lugs broke, in consequence of the shock given by the carriages coming against the leeward girder, and that the columns being thus left unsupported, the bridge fell.

(45.) On the following day, the 6th of May, Mr. Stewart, a mathematician and an engineer, who had assisted Sir Thomas Bouch in designing the bridge, and who, like Dr. Pole, had been present and advising Sir Thomas Bouch throughout the proceedings, was examined, and he agreed with Dr. Pole as to the causes, which had led to the fall of the bridge. He was then asked— *Mr. Stewart's opinion.*

19,003. And generally do you agree with his evidence, and his opinion, that it required something more than any statical wind pressure, that you could have expected to come upon the bridge, to have caused what happened on the night of the 28th December ?—Yes, I do.

19,004. Do you also agree with him that the shock of two of the carriages going at the rate of 25 miles an hour, if they came into collision with the girder, superimposed upon all the normal strains upon the bridge, would be sufficient to cause a failure ?—Certainly.

(46.) Mr. Stewart having stated that "the pier gave way, not from a moment of force, but from a sheering action," he was asked by Mr. Barlow—

19,349. You seem very positive that it was a sheering action ; will you tell us why you think it gave way from a sheering action ?—I think it gave way from a sheering action from examination of the bridge. I saw it, and as Dr. Pole very distinctly explained, I believe the ties were the first thing to give way.

19,350. The lower ties ?—I cannot tell which of them.

19,351. The lower ties would be more strained in proportion to their strength, would they not ?—They would be somewhat more strained.

(47.) He was then asked by the court—

19,368. (*The Commissioner.*) As I understand you, you say you believe that this casualty was due to a sheering action caused by the great pressure of the wind ?—Yes.

19,369. And acting ultimately upon the ties and breaking the ties, and then leaving the columns unsupported, as it were ?—Breaking first the ties, and then the columns would be very weak, and would go over.

19,370. As it has been described, as a pair of rulers ?—Yes.

(48.) Here, Mr. Stewart, in speaking of the ties, evidently meant the cast-iron lugs, for he was asked—

19,384. (*Colonel Yolland to the witness.*) I thought I understood you to say that the first part of the structure that, in your mind, gave way was the lug ?—The first part of the pier that gave way.

19,385. Then that fracture of the lugs was not due to any sheering action there ?—There is a confusion in terms. The sheering action is, in fact, the lateral action carried down to the base.

19,386. I am speaking of the actual fracture of the lug itself, which I understood you to say was the part which, in your opinion, first gave way; there was no sheering action there, was there ?—That was the result of what is called in engineering sheering action.

19,387. Was it not in fact a direct pull that fractured that ?—Yes, it was.

19,388. That is different from what is usually understood to be a sheering action ?—It is the sheering over of the whole pier that I am speaking of; not the sheering action on the lug. I am speaking of the lateral force which is uniformly resisted in every pier from top to bottom, and which is transferred into a tensile train on the ties. It is an engineering difficulty.

19,389. (*The Commissioner.*) If the lugs had been stronger than the ties, perhaps this accident might not have occurred ?—I cannot say that. I think the force was great enough (if my view was correct that the train left the line) to have done a great deal more damage than destroying the pier.

19,390. But at any rate it would have been an element of security, if the lugs had been stronger ?—Of course there is always a weakest point in every structure.

19,391. And that you consider to have been the weakest point ?—I think so.

Mr. Baker's opinion.

(49.) On the same day Mr. Benjamin Baker, an engineer of considerable eminence, was examined, and he concurred generally with Dr. Pole and Mr. Stewart, that it was the lugs which first gave way; and in answer to questions put to him by Mr. Bidder, said—

19,433. You noticed, I think, when you were there, what has been referred to by a good many witnesses, viz., that the cast-iron lugs are mostly broken?—Yes.

19,434. Does that give any indication to your mind as to the nature of the failure?—I think it indicates pretty clearly that the weak point was in the lugs. The lugs failed first, and they would be peculiarly liable to fail by reason of a shock. We know that the slightest shock would break a lug, of course.

19,435. Given cast and wrought iron of approximately equal tensile strength, the cast iron would be the first to fail under a shock, would it not?—Yes, of course.

(50.) And then he is asked—

19,494. You, I believe, have had the opportunity, have you not, of seeing the markings on the girders and the other matters upon which evidence has been given, so that you are able to form an opinion as to whether they were done by the overturning of the carriages or not; but assuming as a matter of fact that the two last carriages of this train going at, say, 25 miles an hour, did overturn and run into the leeward girder, would the sudden arrestment of their momentum, in addition to the normal strains caused by the storm upon the bridge, in your judgment be a shock sufficient to account for the failure of the bridge?—I do not think that would have hurt the girders at all; but I can imagine that in a very high state of tension the lugs would at that time, with their peculiar liability to fail, with a comparatively slight jar, very probably fail with a very slight shock.

19,495. (*The Commissioner.*) You think the lugs would fail from the transmitted shock?—Yes, certainly. I can easily imagine that the blow was transmitted to the bottom of the pier, in the same way that a man falling on his forehead fractures his skull. The shock, in my opinion, would not hurt the girders.

(51.) Mr. Baker then, in answer to questions put to him by Colonel Yolland, gives the following evidence; he is asked—

19,570. Supposing, for instance, you had placed yourself at the centre of one of these 245 feet spans, and cut the two central lattice bars in two, do you imagine that the bridge would have come down?—Certainly not. Within the last twelve months I had to tighten up the centre diagonals of a bridge of about this span, which were perfectly slack.

19,571. Would you go so far as to say that if you cut the two centre lattice bars in each girder, that would not bring it down?—That would not bring it down. I will tell you what I have done. I have run over a girder upon an engine with every one of the web joints unriveted. I did not know it at the time.

(52.) It is needless to say that to have "every one of the web joints unriveted" is a very different thing from having two of the lattice ties and struts cut.

(53.) Lastly, he was asked by Mr. Barlow—

19,572. You have told us that you attribute the coming down of the viaduct to the giving way of a lug; but what made the lug give way; was it undue pressure of the wind, or do you attribute it to a shock or jar?—I think not undue pressure of wind alone, because my opinion is that, taking the strength of the bridge upon the basis of Mr. Kirkaldy's experiments, there was a factor of safety of between 2 and 3; and therefore I think there was a pretty severe strain upon the lug, and then there was some jar.

19,573. Such as would be occasioned by what?—It might be occasioned, as has been suggested, by the train striking the girder.

19,574. (*The Commissioner.*) Or it might have been from defective work?—It might be from a thousand things.

Forces alleged to have caused the accident.

(54.) It will thus be seen that according to those most nearly concerned in building the bridge, and their advisers, two, and only two forces are alleged to have caused its fall, namely, the wind, which all admit was a prime factor in bringing about the accident, and the shock by the train striking against the girder. It may be well, therefore, to see what evidence there is that the train ever did strike the leeward girder before the bridge began to fall; and, if it did, whether it in any way contributed to the accident.

Did the Train strike the Girder?

Which section went first?

(55.) The theory, that the train contributed to the fall of the bridge, proceeds of course on the assumption that the southern section of the high girders, in which the train was found, fell first. If the northern or the middle section fell first, the tilting of the train against the girder, even if it did take place, could not have been the cause of the fall of the bridge. If indeed we could ascertain with certainty in what directions the rails at the expansion joints over piers 33 and 37 were bent, we should know of course, which section fell first; for if we found the rails at the southern ends of the middle and northern sections pulled over to the east, we might safely conclude that the southern section had gone first; on the other hand, if the rails at the northern ends of the middle and southern sections had been pulled over to the east, we should know that the northern section must have gone first. We therefore directed that an

attempt should be made to raise the girders at these two points, and that photographs thereof should be taken and sent to us. Unfortunately, however, the ends of the girders at these two expansion joints were found to have been so much broken up, that it was not possible to determine the question with certainty. Only one piece was raised in a tolerably perfect state, the northern end of the middle section at the expansion joint over pier 37; and from the photographs, which have been sent to us, the rails there certainly appear to have been wrenched to the eastward, thus favouring, as far as it goes, the idea that the northern section of the high girders fell first.

Evidence of eye-witnesses.

(56.) The evidence of the eye-witnesses of the occurrence was also not quite conclusive on the point. First there was Mr. Alexander Maxwell, junior, who told us that, when the bridge fell, he saw three distinct flashes, and that these seemed to be travelling from the south to the north, as though the southern section had fallen first, dragging the other two in succession after it. On the other hand, there was a Mr. William Abercrombie Clark, who saw the accident from very nearly the same spot that Mr. Maxwell saw it, and who also speaks to three flashes, but he says that they were all at the extreme north end of the girders. Next we have Mr. William Robertson, an engineer, and ex-Provost of Dundee, who told us that he saw "two columns of spray, brilliantly illuminated," somewhere between the summit of the bridge and the north end of the high girders, and consequently at the northern section. Lastly, we have the evidence of Mr. Peter Barron, a carriage inspector in the employ of the Caledonian Railway Company, who told us that he saw the lights of the train on the "southernmost part of the high girders;" and that, when they were some two or three spans from the southern end of the girders, he observed a portion of the girder at about one or two spans from the north end go down, then shortly after another portion fell, and then the lights disappeared. If, indeed, this gentleman's evidence is to be relied on, it is clear that the northern section fell first, then the middle, and last of all the southern section with the train upon it.

Other facts bearing on this point.

(57.) Other circumstances also seem to favour the conclusion that the northern section fell first; for instance, all the sections, as we learn from Mr. Law, appear to be set about 18 inches over to the north shore, and the columns also for the most part incline in that direction, as though the fall had been in that direction. There is also a fact connected with the speed of the trains and the gradients of the bridge, to which we shall presently have to refer, and which seems to point in that direction. And if it really was the case that the northern section went first, there is an end of these gentlemen's theories that the fall of the bridge was in any way due to the train having struck the leeward girder.

Marks on the leeward girder.

(58.) It was said, however, that there are marks on the girder which show that the train struck the leeward girder before the bridge began to fall. It seems that Mr. Thomas Napier Armit, who has been employed under Sir Thomas Bouch's instructions to raise the fallen girders, having discovered certain marks or scorings on one of the lattice bars of the leeward girder, Mr. Charles Meik, Sir Thomas Bouch's assistant, was sent down to Dundee to examine and make a sketch of them; and this sketch was brought in by him during the progress of the inquiry. Subsequently other lattice bars with similar marks and scorings upon them having been discovered, Sir Thomas Bouch constructed a plan, which he has forwarded to us in a letter dated the 27th May ultimo, after the conclusion of the examinations, and which he says confirms his theory "that at least the guard's van and the second-class carriage next it had been in "contact with the east girder, before the bridge fell." The plan shows a number of marks or scorings on the inside of eight consecutive lattice bars, which we are told formed part of the leeward girder immediately in the rear of where the train was found. The marks or scorings are parallel, and cover about a foot of each lattice bar, the lowest being about 11 feet and the highest about 12 feet above the line of the rails. We were told, however, by Mr. Dugald Drummond, the locomotive superintendent of the company, that the top of the second-class carriage, by which these marks are supposed to have been made, would be, as nearly as possible, 10 feet above the rails, so that it is somewhat difficult to understand, how it could, when the bridge was upright, by being tilted against the girder, as is suggested, have made these marks or scorings at a height of from 11 to 12 feet above the rails. Moreover, to make these marks upon eight consecutive lattice bars, the carriage must have passed over three bays or openings, each more than 25 feet wide; and if the carriage was at the time leaning with any force against the girder, we are at a loss to understand why, seeing that it was only 22 feet long, it did not fall through one of these openings; and

if it was not leaning against the girder with any force, it is equally difficult to understand how it could have contributed to overthrow the bridge.

Could the tilting of carriage have done any harm?

(59.) But supposing that the second-class carriage and guard's van did tilt, as is suggested, against the leeward girder, is there any reason to suppose that it could have done it any harm? We were told by Mr. Dugald Drummond (Q. 18,183) that the second-class carriage was a very light carriage, very lightly constructed, and that it was in fact the only light carriage "in construction, and of itself, that there was " in the train." To suppose then that the top of such a carriage could have done so much injury to the bridge, as to have caused more than 1,000 yards of it to fall, seems in the highest degree improbable; we are rather disposed to concur with some of the witnesses, who thought that it would have "gone off like match-wood," without doing the slightest injury to the girder.

Character of the marks.

(60.) And after all, what is the character of these marks or scorings, which we are told give evidence of a shock of such terrible force? Mr. Armit was asked by Mr. Bidder to describe them, and his answer was (Q. 17,491), "They are black, and " in passing your finger over them you can feel that there is more than the paint— " that even the iron bears a graze; there are hard grazes, the heads of the rivets " are very hardly rubbed; in passing your finger over you can feel a distinct hollow; " and over the heads of the rivets there has been a very hard graze indeed." Mr. Meik's evidence was to the same effect; on being asked by Colonel Yolland, (Q. 17,341), " Are these scorings that you speak of indents in the iron?" he answered, "Not exactly " indents; the paint is all scratched off. There are some scratches in the iron too, but " they are not deep."—(Q. 17,342.) "A thirty-second part of an inch, or a sixty-fourth " part of an inch?—I did not measure them, but they are very slight." It is certainly inconceivable that a blow, which was hardly more than sufficient to take the paint off, and which Mr. Meik, a civil engineer and a very competent witness, was not prepared to say had scratched the iron to the depth of one sixty-fourth of an inch, and which he described as "very slight," should have produced such results. It seems to us that these marks or scorings could hardly have been made, before the bridge had begun to fall; and that even if they had been, they were not sufficient to have caused the fall of the bridge. It seems more probable that they were made by the train, after the bridge had begun to fall over, when the train would necessarily be thrown upon the leeward girder, and not having yet lost all its forward motion, it would not unnaturally make such marks as we see.

Other reasons considered.

(61.) It was, indeed, suggested that there were other marks lower down, which might have been made by the frame of the carriage, which is much stronger than the upper part of it; and our attention was called to a photograph of the second-class carriage, which showed the after buffer on the west side to have been much injured; and it was suggested that this might have been done by the guard's van, when the second-class carriage was brought up by the fore part of the frame striking the lattice bar. But if so, the fore part of the frame, where it is supposed to have come against the lattice bar, should have shown marks of the collision, but it seems from the photographs to be quite uninjured. There is therefore no reason to think that the frame of the carriage ever came in contact with the girder, at all events before the bridge began to fall.

State of engine when found.

(62.) There is also the fact that, when the engine was found after the casualty, the throttle valve was full open, the reversing lever "standing in the sixth notch from " full forward gear, or in the third notch from centre." Now, if any part of the train had left the line or been tilted over against the leeward girder, as is suggested, before the bridge began to fall, there can be little doubt that the engine-driver would have seen it, and have at once reversed the engine full speed, so as to bring the train to rest as soon as possible; and the fact that he had not done so, strongly confirms us in the opinion that the train must have been in position on the rails, when the bridge first began to give way.

(63.) The suggestion then that the train struck the leeward girder, before the bridge began to fall, and that even if it did, it would have contributed to its fall, being in our opinion disproved, the next question to be considered is whether the accident can fairly be attributed to the violence of the gale alone.

Wind Pressures.

Dr. Pole and Mr. Stewart's views.

(64.) In a paper prepared by Dr. Pole and Mr. Stewart, at the instance of Sir Thomas Bouch, which will be found in the Appendix, and in which the stability of the

bridge and its capacity to resist the pressures, which might be brought upon it, are very fully discussed, we are told that "the ordinary source, from which estimates of "the force of the wind have been usually taken, is the well-known table presented "by Smeaton to the Royal Society in 1759, which gives a pressure per square foot "of 6 lbs. for high winds, 8 or 9 lbs. for very high winds, and 12 lbs. for a storm "or tempest. There are," they say, "still higher figures for great storms or "hurricanes, but it is stated that these are of doubtful authority, and only apply "to tropical meteorology." They then proceed as follows: "Referring to the "authentic records of wind pressure gauges in the heaviest storms that have occurred "for many years, it has been found that upon very limited surfaces, and for very "limited times, the pressure of the wind does amount sometimes to 40 lbs. per "square foot, or in Scotland probably to more. But the best authorities, who "have studied these gauges, have arrived at a confident opinion that such high "pressures are only momentary, arising from some irregular whirlings of the air, "which extend to no great distance. And if it is considered as a practical matter "what a lateral pressure of 40 lbs. per square foot really means, and what effect it "must produce, common experience must render it very doubtful whether any such "pressure can be sustained by objects ordinarily exposed to the wind's action." For these reasons, they say, "in designing the bridge, a maximum wind pressure was "assumed, acting over the surface of a span and pier, equal to about 20 lbs. per "square foot, (being more than double what Smeaton allowed for a very high wind;) "and the dimensions were calculated for this pressure with the usual margin of "safety."

Sir Thomas Bouch's views.

(65.) Sir Thomas Bouch indeed did not endorse the statement of Dr. Pole and Mr. Stewart that "in designing the bridge, a maximum wind pressure was assumed, "acting over the surface of a span and pier, equal to about 20 lbs. per square "foot;" for he told us in answer to questions put by Mr. Trayner and by the Court (Q. 16,939 and 16,940) that in designing the bridge he had not made any allowance for wind pressure "specially." What indeed Sir Thomas Bouch's opinion was, as to the maximum wind pressure, when he designed the Tay Bridge, we do not know. We are told, however, that on the occasion of Sir Thomas having designed a bridge to cross the Firth of Forth, the Astronomer Royal was applied to for information as to the amount of wind pressure, for which allowance should be made; and in reply the Astronomer Royal stated, in a letter dated the 9th of April 1873, that, although "upon "very limited surfaces, and for very limited times, the pressure of the wind does "amount sometimes to 40 lbs. per square foot, or in Scotland probably to more," yet that, looking at the character of that bridge, which was a suspension bridge with two spans of 1,600 feet each, the greatest amount of pressure, to which it would probably be subjected on its whole extent, would, in his opinion, not be more than 10 lbs. per square foot. Sir Thomas Bouch told us that, after the receipt of that Report, he had a "different idea of the force of the wind." It is, however, to be observed that that Report is dated April 1873, nearly two years after the contract with Messrs. De Bergue for the building of the Tay Bridge had been signed, so that, although it may have had some influence on his mind, when he was altering his plans, it could have had none, when he was designing the bridge.

Mr. Baker's views.

(66.) Mr. Baker, again, who seems to have devoted much time and attention to the subject of wind pressures, and who is also a civil engineer of eminence, told us that for the last 15 years he had (Q. 19,480) "looked very carefully for evidence of any structure "capable of standing an uniform pressure of 20 lbs. per square foot which had been "blown down," and that he had never found a single instance; (Q. 19,487) that there were hundreds of buildings in this country, that would be blown down with a pressure of 20 lbs. to the square foot, and miles of wall on the edges of cliffs and on open downs, which would be blown down with a pressure of even 13 lbs., and which had remained standing for 30 and 40 years; and that in his opinion the pressure over one span of the high girders could hardly have exceeded 15 lbs. per square foot, and he ridiculed as mere idle talk the idea of "a wind pressure of 40 lbs. or anything like it."

Maximum wind pressure.

(67.) Now it appeared to us that, in order to arrive at a correct judgment as to whether the violence of the wind alone could have overthrown this bridge, it would be well to obtain the best information as to the greatest known pressure of the wind, and to see how far it agreed with the opinions which had been expressed by Sir Thomas Bouch, Mr. Baker, Dr. Pole and Mr. Stewart. We accordingly applied to the Astronomer Royal, to Professor Stokes, of Cambridge, and to Mr. R. H. Scott, of the Meteorological Office, who kindly attended, and gave us some very valuable and interesting evidence on the subject.

Professor Stokes' views. Measures of wind pressure.

(68.) According to Professor Stokes, who has given much attention to the subject of the motion of fluids, more perhaps than any person in this country, there are two measures of wind pressure, which it is most important to distinguish, but which are very frequently confounded, and that very serious errors frequently result therefrom. One of these pressures is that, which would be measured by the height of a column of fluid in an inverted syphon tube, the mouth of which is exposed to the direct action of the wind; this he called the "standard pressure." The other is the pressure on a plate, which can be measured by an Osler's anemometer; what, he said, happens in this case is that "the air in passing the edge breaks into eddies, which, mixing with the still air behind, drag it along," producing a partial vacuum behind the plate. He told us that it had been found from experiment that the pressure on a plate is much greater than the "standard pressure," measured hydrostatically; according to Sir Henry James it is 100 per cent. greater, but Professor Stokes thinks that it would be safer, on an average of the best authorities, to take it at 80 per cent.

Velocity of wind.

(69.) Professor Stokes, however, told us that it is much more common to measure the force of the wind by its velocity, and that this is done by a Robinson's cup anemometer, which registers the number of revolutions, which the cups make round an axis in a given time. He said that the usual practice was to allow a factor of 3 for the relation of the velocity of the cups to that of the wind, but that he thought that we should not be far wrong if we took it at 2·4. This would no doubt give a somewhat lower speed for the wind than that usually recorded at observatories and stations; but even with this reduction he thought that there was no doubt that velocities of 100 miles an hour were not unfrequently attained, more especially in gusts.

Relation between velocity and pressure.

(70.) It becomes, therefore, very important to translate velocity into pressure, or in other words to ascertain the relation subsisting between the velocity and pressure of the wind. Now Professor Stokes told us that it had been found by experiment that a velocity of 20 miles an hour gives a standard pressure of 1 lb. per square foot; that he had calculated what it would be by theory, and that the results were almost exactly the same. And as the pressure varies with the square of the velocity, if a velocity of 20 miles an hour gives a standard pressure of 1 lb. per square foot, a velocity of 60 miles an hour would give three times three or 9 lbs., and a velocity of 100 miles an hour of five times five or 25 lbs. per square foot. This, however, would be the standard pressure. Adding, therefore, 80 per cent. we get the pressure on a plate for a velocity of 60 miles to be 16·2 lbs., and for 100 miles to be 45 lbs.; or, according to Sir Henry James, 18 lbs. and 50 lbs. respectively.

Duration and extent of high pressures.

(71.) Professor Stokes was pressed very strongly by Mr. Bidder as to whether such violent gusts as these, which would produce a pressure of 50 lbs. on a plate, would not be only momentary, and whether they would extend over more than a few feet in width; but he answered (Q. 16,248) "a very heavy gust will not be a mere "momentary thing, though it will not be of any great duration ordinarily; it will "sometimes go on for two or three minutes blowing very heavily indeed." And as regards extent Professor Stokes stated that, when we hear of "a heavy gust being confined to a very narrow track," he considered that "narrow" meant having a breadth of a few hundred yards, of which he said there were many instances on record. He added that there would probably be a relation between the duration and extent of a gust, and thus one, which had lasted for half a minute, would probably "extend over a considerable space laterally."

Astronomer Royal's opinion.

(72.) This very valuable and interesting evidence of Professor Stokes as to the force, the duration, and the extent of a gust of wind was fully confirmed by the Astronomer Royal; who was then asked by Sir Thomas Bouch's counsel, how he could reconcile that opinion with the opinion given by him in 1873, that the maximum pressure over the area of one of the spans of the Forth Bridge would probably not exceed 10 lbs. per square foot. Mr. Bidder contended that the term "very limited spaces" must mean a point or only a few feet, but the Astronomer Royal stated that that was not at all his meaning, and that it might mean 100 or 200 feet, or even more, and that in his opinion you might have a maximum pressure of 40 or 50 lbs. over an area of 245 feet, the extent of one of the spans of the Tay Bridge, but that it did not necessarily follow that you would have the same pressure over 1,600 feet, which was the length of one of the spans of the Forth Bridge. He said that the circumstances of the two bridges were quite different, and that that had materially influenced his opinion; that the Forth Bridge, which was a suspension bridge, might be pushed on one side by a high pressure, and would, when the pressure was taken off, return to its original position, without having sustained any injury; but that it would be quite different with such a bridge as the Tay Bridge, standing, as he

described it, "on high stilts," for if once blown on one side and out of position, it could not recover itself, but must come down.

(73.) Mr. Scott, indeed, seemed disposed to put the velocity of the wind even higher than either the Astronomer Royal or Mr. Stokes had done, taking a factor of 3 instead of 2·4 given by Professor Stokes; and he gave instances of some very violent storms, amongst others one that had occurred at Walmer, where for a width of 450 feet to 700 feet it had carried everything before it. He also told us that about the time when this bridge fell, the velocity of the wind at Glasgow and Aberdeen, as recorded by anemometers at those places, with a factor of 3, was for some minutes little, if at all, less than 100 miles an hour, giving therefore, according to Mr. Stokes, a standard pressure of 20 lbs., or a plate pressure of about 45 lbs. *Mr. Scott's opinion.*

(74.) We think, therefore, after the evidence of these gentlemen, that there can be no reason to doubt that there may be wind pressures of 45 lbs. and even 50 lbs. in this country; and the difference between them and Messrs. Pole, Stewart, and Baker is probably due to the latter having taken the standard pressure instead of the pressure on a plate; a standard pressure of 25 lbs. being, as we have seen, equivalent to a plate pressure of 45 lbs. according to Professor Stokes, and of 50 lbs. according to Sir Henry James. We may add that the practice in France appears to be to allow 55 lbs. for wind pressure, and in the United States 50 lbs. And although there seems to be no settled practice in England on the subject, Mr. Brunlees told us that he allowed 30 lbs. for wind pressure, and even Mr. Baker himself said that he allowed 28 lbs. *Probable maximum wind pressures.*

Storm of 28th December.

(75.) But although in rare and exceptional cases there may be a wind pressure of 40 and even 50 lbs., and for which, therefore, it would be proper to provide, it does not at all follow that the gale of the 28th December last was a storm of that exceptional character. *Its character.*

That it was a very violent storm can admit of no doubt, for some of the witnesses speak of it as having been more violent than any that they had ever before experienced on the Tay. On the other hand one gentleman, a Mr. Charles Clark, living on Magdalene Green, near the northern end of the bridge, and who has been in the habit of noting and registering the state of the weather at Dundee for the last 14 years, told us that during that time he remembered about four storms equally violent. But perhaps the most reliable information as to the violence of the wind on the evening in question is to be found in the evidence of the officers of the training ship "Mars," which was at the time lying at anchor in the Tay about three-quarters of a mile to the east of the bridge; and as the wind at its height was blowing nearly straight down the river, it may reasonably be expected that they would feel the full force of the gale. According to Captain Scott, her commander, it was blowing a whole gale, with what he would call a force of 10 (12 being the maximum), and in the squalls, he said, it was, perhaps, from 10 to 11. He told us, however, that he had experienced more severe storms, even in this country, and one or two "quite equal "in force in the last two or three years," during the time that he had been stationed in the Tay. Captain Scott also told us that he had had a great deal of experience in the West Indies and the China Seas, and that during his career he had frequently registered storms of the force of 11 to 12, very much more violent than that of the 28th of December last; as he observed, (Q. 1308) "there is a marked difference in the " registering, the higher you go in figures, the more marked is the difference; there is " a vastly greater difference between the figures 11 to 12, than there is between the " figures 9 and 10." Captain Scott's evidence was confirmed by Edward Batsworth, the Gunnery Instructor, and by Hugh McMahon, the Seaman Instructor, on board the "Mars," the two men by whom the log was kept. There was also another very competent witness, Admiral Dougall, who spoke of the extreme violence of the gale on the night in question; and who told us that its force as compared with those which he had encountered in the China and West Indian Seas, would be in about the proportion of 75 or 78 to 100, or about three-fourths of their intensity.

(76.) Whilst, then, we are quite prepared to admit that it was a very violent storm, there is nothing to show that it was exceptional in its character, or that it had anything like the intensity of a West Indian cyclone or a Chinese typhoon. A storm, which, according to Captain Scott, had been equalled in its intensity by one or two others, which had occurred during the last two or three years, and according to Mr. Clark, by no less than four within his own memory, ought hardly to have overthrown a bridge within 18 months of its having been opened, if only reasonable provision had been *Violent, but not exceptional.*

taken against it. It becomes therefore important to ascertain what provision was made against wind pressure, or, in other words, what amount of lateral force would have been required to overturn this bridge, assuming it to have been properly constructed.

Force required to overturn the Bridge.

With and without holding-down bolts.

(77.) According to Dr. Pole and Mr. Stewart, assuming the bridge to have been properly constructed in all respects, it would have required, if not held down at its base, a lateral force of $34\frac{1}{3}$ lbs. to the square foot, applied at right angles to its direction, to have overturned it; and with holding-down bolts, from 60 lbs. to 70 lbs. According to Mr. Law a force of a little under 33 lbs. would have been sufficient to overturn it without holding-down bolts; and with holding-down bolts, rather more than 64 lbs. These estimates, it will be seen, do not differ very much, and it may therefore be fairly assumed that, if the bridge had been properly constructed, and in accordance with the plans and specifications, it would have required a force of from 60 lbs. to 70 lbs. applied directly at right angles to have overthrown it.

Factor of Safety.

(78.) We can see now why it was that Sir Thomas Bouch's Counsel was so anxious to show that the maximum wind pressure over the area of one of these spans must have been so small, and that the term "very limited surfaces" must have meant a point, or at the most only a few feet, and not some hundreds of feet, which may well be called a "very limited surface" compared to the whole width of the storm. For, if the maximum wind pressure over one of these spans was only 10 lbs. to the square foot, and the force required to overthrow the bridge was from 60 lbs. to 70 lbs., we should have had a factor of safety of between 6 and 7, which would be a good margin; and even if the maximum pressure was 20 lbs., there would still be a factor of safety of over 3. On the other hand, if the wind pressure over an entire span could ever be as much as 40 lbs. or 50 lbs., the margin of safety would be ridiculously small, not a half, and the bridge from the first would have been quite unsafe, the usual factor of safety we are told being 4 or 5.

(79.) Assuming, however, the bridge to have been properly constructed, and to have been capable of resisting a wind pressure of 60 lbs. to 70 lbs., it is difficult to see how the wind alone could have overthrown it, even if it had been at its maximum of 40 lbs. or even 50 lbs. to the square foot. It would seem therefore that we must look to something beyond the mere wind pressure to account for its fall; and this we are told is to be found in certain faults and defects in the construction.

Defects in the Construction.

Charges made at Dundee.

(80.) In the course of the examinations at Dundee, charges of a very grave and compromising character were made as to the quality of the iron, and the workmanship at the Wormit Foundry, which it was necessary to inquire into, seeing that it was at the Wormit Foundry that all the columns for the high girders were cast. And although all these charges were not fully established, enough has in our opinion been proved to show that there were defects introduced into the structure, which should never have been there, and which certainly did very seriously affect its stability. We will proceed to inquire what they were, and whether they are not sufficient to account for the accident.

Quality of the iron.

(81.) And first as regards the iron, which was said to have been of inferior quality, and from which we are told it would not be possible to obtain good castings. It seems that the iron was for the most part Cleveland iron, sent specially from Middlesbrough by Messrs. Hopkins, Gilkes, & Co., the contractors. Like all Cleveland iron, it was more sluggish than Scotch, and required to be raised to a higher temperature to make it flow freely, without which it would be impossible to get good castings, particularly in the lugs and protuberances on the columns. The result was that it was not popular with the Scotch workmen, who were accustomed to work with a more ductile metal, and they complained that a sufficient quantity of Scotch scrap was not mixed with it. Even Mr. Beattie, the engineer, who had for some time the control of the foundry works at Wormit for the contractors, seems to have thought that the introduction of some more Scotch scrap would have been desirable, and suggested that this should be done, but his suggestion was not acted upon. The result was that the iron, although shown by Mr. Kirkaldy's tests to be fairly good in quality, gave, owing to its sluggish character and to its not being sufficiently heated, in many cases very defective castings. Thus, there were not unfrequently found in the columns, what are called "cold shuts," caused by the metal becoming chilled,

before it had got round the mould; so that, when the two upper edges came together, they would not unite, but left a longitudinal fracture in the side of the column. Scabs also were formed by the sand of the mould becoming displaced, mixing with the metal, and floating to the surface, leaving an unsound place in the column, which occasionally seems to have been filled up with lead or a material called "Beaumont egg," a mixture of resin, steel filings, &c. Owing also to the flask or core of the mould having been allowed to shift, the columns were frequently cast of very unequal thicknesses. It is true that many of the columns, in which these defects existed, were broken up; some, however, were passed, and were introduced into the structure; to what extent it is impossible to say, the greater part of the columns of the high girders being still at the bottom of the river. There is, however, conclusive evidence that some of the fallen columns were very defective, having scabs and unsound places in them; and specimens were produced showing the metal on one side of the column to have been occasionally only $\frac{5}{8}$ths of an inch thick, while on the opposite side it was as much as $1\frac{3}{8}$ths thick. Indeed Sir Thomas Bouch admitted that there were some of the columns, which he would not have allowed to pass, had he known of them. Under ordinary circumstances, where there is a large margin of safety, such defects in the castings might not be very important, the margin of safety being intended to cover them; but in the present case, where the margin of safety was absurdly small, they cannot altogether be overlooked.

Cast lugs.

(82.) But it was in the lugs more especially that the principal defects existed. They were, as we have said, cast with the columns; owing, however, to the sluggishness of the metal, it did not readily flow into the pockets or hollows left to form the lugs. The consequence was that many of the lugs came out in an imperfect state, and in some cases an attempt was made to "burn on," as it is called, a fresh lug by making a mould for the purpose, and pouring in a sufficient quantity of molten iron. It is obvious, however, that perfect cohesion between the parts could hardly be obtained in this manner, for, as the metal cooled, it would necessarily shrink, leaving a space between the lug and the flange, or between the lug and the shaft, and there was strong evidence that this was so. We were assured, however, that none of the columns, on which lugs had been so burnt, were introduced into the structure; and that they had only been used to raise the girders into position, and had then been removed.

Holes cast in lugs.

(83.) But it was in casting the "holes," through which the bolts, which held the ends of the struts and tie bars, passed, that the greatest mistake was made. These holes were cast in the lugs, and were already made, when they issued from the mould. We were told, however that it is almost impossible to prevent the workmen from casting the holes conical, as the cores can then be more readily removed; and accordingly we find that the holes in the lugs were for the most part, if not entirely, cast conical. The result was that the bolts, instead of having a plain surface to rest upon, as they would have had, if the holes had been drilled or made cylindrical by riming, or drilling, bore only on one edge, and when a strain came upon them, they would of course give, until they got a bearing upon the sides of the holes. That this was a defect, and a very serious defect, was admitted by Sir Thomas Bouch himself in the following answers, which he gave to the questions put to him by the Court:—

Sir Thomas Bouch's evidence on the point.

17,137. (*The Commissioner to the Witness*). You told us also that the bolt holes ought to have had the sides as you say, perfectly square or parallel?—They ought to have been.

17,138. And if you had known they were not, you would have had them rimed or drilled?—I certainly would. Probably if I had known it earlier, before much of the bridge was built, I should have had them squared—I might have had them rimed out, but I would have calculated the strength of the lug before I began to take the metal out.

17,139. When you had them cast, you could have had the holes cast rather smaller, and you could have had them rimed out?—Yes.

17,140. That would have been better?—That would have been better. It is not in the specification. The specification says that the holes in the flanges are to be drilled, and it certainly is an omission in the specification so far as the holes in the lugs are concerned. I think it was a fair inference that the holes should have been drilled.

17,141. Surely it was intended that the holes to contain the bolts should not be conical?—Yes.

17,142. It says: "All bolts to be made of Low Moor iron, or such other make as shall be specially sanctioned by the engineer, and to be neatly finished, head and nut, and not projecting more than $\frac{1}{2}$ an inch through the nuts; to be carefully forged and screwed, and made to fill the bolt holes"?—Yes.

17,143. So I suppose there is no doubt whatever, if that had been carried out, you would have had these bolt holes with the sides perfectly level and perfectly parallel?—Most decidedly.

17,144. It was a defect not to have them so?—It was.

17,145. The defect I understood you to be this; that the bolts would give till they got a fair bearing upon the sides of the holes?—Yes.

Bolts did not fit truly.

(84.) It should also be observed that the holes from being cast would be necessarily irregular in shape and position, and as it would be quite impossible to cast them

quite true to size, they were made $1\frac{1}{4}$ inches, while the bolts which went through them were only $1\frac{1}{8}$ inches in diameter. The effect of these three things, namely, the giving of the bolts so as to get a bearing on the sides of the holes, the irregularity of the holes in shape and position, and the holes being larger than the bolts, was to give a certain amount of play to the ends of the ties and struts, which held the columns in position. Moreover the conical form of the hole converted the hold on the lug into a wrenching strain on one side of it; so that it was found, under Mr. Kirkaldy's tests, that, when the force was applied in the same direction as when in position on the column, and by a steady pull, and without any shock, the lug was able to bear only one third of the pressure, which it should have done according to the amount of its sectional area.

Holes in the flanges of 18-inch columns.

(85.) Another serious defect in the construction of the bridge was in the formation of the flange holes of the outer or 18-inch columns. It seems that the holes in the flanges of the inner or 15-inch columns were drilled by a machine, and they would consequently be true to position and cylindrical in form. When, however, they came to make the 18-inch columns, the machine, which had been employed for drilling the holes in the 15-inch columns, would not serve for the 18-inch columns, and it was not thought necessary to make a machine expressly for the purpose. The consequence was, that the flange holes of the 18-inch columns had to be cast, with the same results as in the case of the holes through the lugs, namely, that they were conical in shape, irregular in size and position, and gave play to the bolts passing through them, which thus ceased to be steadying pins to the columns, and bore upon only one edge of the holes. According, too, to Mr. Beattie, under whose superintendence these columns were cast, the holes were cast $1\frac{1}{2}$ inches in diameter; whilst the bolts were $1\frac{1}{8}$ inches (Q. 10,048). This was the more serious, seeing that each of the 18-inch columns had to bear not only double the superincumbent weight, that any of the 15-inch columns had, but also the greater part of the wind pressure.

Other defects.

(86.) Our attention was also called to other defects in the construction; as for instance, that the ties were secured by screwed bolts instead of pins, so that they yielded with a much more moderate strain; that the gibs and cotters were in many cases roughly forged, and the slotted holes for their reception were roughly formed, which would cause a slackening of the ties by the yielding of so many badly fitting surfaces; that the struts were badly fitted, and did not abut against the columns; and that the attachment of the L girder to the 18-inch columns was very imperfect and insecure. The result of all these several defects, and especially of the play and bending of the bolts in the holes, would be to loosen the ties, so that, when a lateral pressure came upon the columns, they would be less capable of offering a resistance, and would very readily get out of shape.

Supervision at the Wormit Foundry.

(87.) And here it may be well to inquire what kind of supervision was exercised over the works at the Wormit Foundry, where these columns were cast, for it is difficult to understand, how the numerous defects, to which we have called attention, should have been allowed to pass, if there had been proper and competent persons to superintend the work.

The Contractors' Officers.

(88.) And first as regards the contractors. The person, who had the chief control of the works, on behalf of the contractors from first to last, was Mr. Gröthe. Under him were two chief assistant engineers, namely, Mr. Frank Beattie, who went to the works at the latter end of 1873, and remained there until about 12 months before the bridge was opened; and Mr. W. G. Camphuis, who went in August 1873, and remained until October 1878, some months after the bridge had been opened. From July 1874 to April 1875, a man named Hercules Strachan was the foreman moulder; and after he was dismissed, and until the works were completed, Fergus Ferguson. The practice seems to have been for the columns, as soon as they came out of the moulds, to be passed over to the dressers to clean them and take off any excrescences; they then went into the turner's hands to turn the flanges, and in the case of the 15-inch columns to drill the holes in them; after which, if they were considered sufficiently sound, they were painted, and were sent off as they were needed to the bridge. From 160 to 200 of the columns were made by Hercules Strachan, the rest by Fergus Ferguson.

(89.) Mr. Gröthe had of course the general superintendence of the works, but according to his own account having no special knowledge of ironwork, the Wormit Foundry was put under the management of Mr. Beattie, who, we are told, had

had experience in ironwork; but Mr. Beattie had other duties to perform, and could not therefore be much at the foundry; nor does he appear to have tested the columns by hydraulic pressure or in any other way, which would have insured the detection of any unequal castings, and any defects in the columns; he trusted to what he could discover by looking at them externally, and tapping them with a hammer. When however he left, the inspection of the foundry was entrusted to Mr. Camphuis, who it is admitted had no practical or special knowledge of ironwork, and his duties in connexion with the foundry were consequently "more of an administrative than of a technical kind;" to use Mr. Gröthe's own words, "His" (that is, "Mr. Camphuis') "duties were to see to the stores, and to anything that was wanted, "and to exercise as much judgment as he could in going over the castings, but he "was not a practical foundry man." The result of course was, as Mr. Gröthe admitted, that the chief responsibility for the columns being turned out in a properly sound condition, at all events after Mr. Beattie left, rested with Fergus Ferguson, the foreman moulder. That this was a condition of things, which ought not to have existed, can admit of no doubt whatever. It is true that Fergus Ferguson and the rest of the workmen were paid, not by the piece, but by day work; at the same time he would naturally be disposed to pass columns, which a more independent person would not have deemed sufficiently good, for the fewer columns he broke up, the greater testimony would it be to his skill as a workman. Mr. Gröthe told us that he discovered a column, which had been passed to go into the bridge, and which he ordered to be broken up, owing to defects which he found in it. This was whilst Fergus Ferguson was the foreman moulder, so that in that instance Fergus Ferguson must either have knowingly passed bad work, or have passed it without examining it. Practically, therefore, there was no supervision of the works on behalf of the contractors, at all events after Mr. Beattie left, and the answers which Mr. Camphuis gave to the questions which were put to him on the subject, showed how unfit he was to have the superintendence of the works, and how incapable he was to have detected any defects which might have existed.

Charge left with foreman moulder.

(90.) What then was the superintendence exercised by Sir Thomas Bouch and his assistants over the foundry works at Wormit? So far as we can see, none whatever. The person immediately under Sir Thomas Bouch was Mr. Paterson, a gentleman no doubt of large experience, but perhaps somewhat too advanced in years for a work of this kind. He had an office at Dundee, but resided, we are told, at Perth, having certain duties connected with the railway station there. Under him were two gentlemen, Mr. Ralph and Mr. Butler. Now neither of these gentlemen has been produced before us. Mr. Paterson, we are told, is paralysed, and therefore could not attend; but where Mr. Ralph and Mr. Butler are, we do not know. There were also a Mr. Wemyss, who we are told is now in South Australia; and Mr. Noble, whose duties were confined to the brickwork and earthworks. As a fact, however, not one of these gentlemen, so far as we are aware, ever made it a practice to inspect the works at the Wormit Foundry, to see whether the columns were or were not properly cast, or whether the bolt-holes, on which so much depended, were or were not cylindrical. Sir Thomas Bouch seems to have left it to Messrs. Hopkins, Gilkes, & Co.; they left it to Mr. Gröthe, and he left it to Fergus Ferguson. With such supervision, or rather we should say with the absence of all supervision, we can hardly wonder that the columns were not cast so perfectly as they should have been, and that the fatal defects in the lugs and bolt-holes should not have been pointed out.

Supervision by Sir Thomas Bouch and his officers.

(91.) The best proof, perhaps, of the total want of any effective control and supervision over the work is afforded by the contradictory statements made by the witnesses as to the person, who finally decided the thickness of the metal, which was to be put into the columns. Fergus Ferguson, the foreman moulder, told us that the specified thickness both of the 15 and of the 18-inch columns was to be 1 inch, but that he had cast them all above that, some $1\frac{1}{8}$ inch, some $1\frac{3}{8}$ inch (Q. 8034); and on being asked by whose authority he did it, he said, (Q. 8035*a*) "I just took it upon my own responsibility to do so. I thought it better to give an extra thickness than have them the other way." When, however, Mr. Gröthe came to be examined, he stated (Q. 13,727) that Fergus Ferguson had not taken it upon his own responsibility, for that he (Mr. Gröthe) had instructed him to do it; he said, (Q. 13,728) "Ferguson's words would be exactly my words, because I took it upon my responsibility for the very reason he states." Further on he stated (Q. 13,731) that the first orders were that the 15-inch columns were to have 1-inch thickness of metal, and the 18-inch columns $1\frac{1}{4}$ inch; but that that was afterwards altered, and orders were given that they should all have 1-inch of metal. He

Thickness of metal in the columns.

was then asked whether this applied to both descriptions of columns, and he answered, "Yes. I had no doubt myself that the 1-inch metal would not be sufficient for that "column, but as the diameter of this column (pointing to the model) is larger, and as "the upward pressure of the metal, when it is poured into the mould, increases, "of course, with the size of the core, without saying anything about it, I told "Fergus Ferguson to make them $1\frac{1}{8}$ inch, in order to allow for any inequality, "which I was almost sure would take place, in consequence of the increase "of the size of the core." It was stated by counsel that, when Mr. Gröthe said that he "had no doubt that the 1-inch metal would not be sufficient," he meant that he thought that it would be sufficient; this may be so, although it hardly seems to agree with the latter part of his answer. When, however, Sir Thomas Bouch came to be examined, he stated that it was by his orders that the 18-inch columns had been made $1\frac{1}{4}$ inches thick; and Mr. Stewart told us (speaking from an entry which he made in his diary at the time) that, to the best of his belief, and so far as his knowledge went, it was on the 6th of April that Sir Thomas Bouch "decided to make the outer columns $1\frac{1}{4}$ and the inner columns 1 inch thick;" but whether Sir Thomas Bouch gave the order for it to be done, is not quite so clear. Whether then the increase in the thickness of the columns was made by Fergus Ferguson on his own responsibility, or by Mr. Gröthe on his responsibility, or whether Sir Thomas Bouch ordered it; or, again, whether it was both the outer and the inner columns, the metal of which was increased in thickness, as Fergus Ferguson said, or whether only the outer columns, are questions which are left in the greatest doubt. The statement, however, that is made that either Mr. Gröthe or Fergus Ferguson should, as agents of the contractors, have taken it upon themselves to increase the thickness of the columns, without communicating the fact to Sir Thomas Bouch, seems somewhat strange, seeing that payment was to be made according to the weight of the metal supplied, and that an increase of 25 per cent. in the thickness of these columns would increase the cost considerably.

Maintenance of the Bridge.

Sir Thomas Bouch appointed to superintend the maintenance.

(92.) And now let us see what steps were taken to maintain the bridge, in an efficient state. It seems that, after the bridge was completed, an arrangement was made by the company with Sir Thomas Bouch, that in consideration of an annual payment to him of 100*l.*, he should continue to watch over its condition. The company's engineer was to have charge of the permanent way, but all below it, including of course the piers, was to be under Sir Thomas Bouch's supervision; and that arrangement was in force when the accident occurred. Sir Thomas Bouch's chief anxiety appears to have been, not so much for the iron work of the bridge, as for the foundations of the piers; and accordingly Mr. Noble, with a staff of men, was placed at his disposal for the purpose of taking soundings, and of filling up any holes that might be found about the piers by the scour of the river. As a fact this proved to be a very necessary precaution, and large quantities of stone and ballast were, under Sir Thomas Bouch's directions, thrown into the river round the piers to prevent the foundations being undermined.

Chattering of the tie bars.

(93.) It seems that so early as September 1878, the railway having been opened for passenger traffic in the preceding June, Mr. Noble, whilst employed in taking these soundings, heard what he described as a chattering of the tie bars, and on climbing up the piers he found some of them loose. He accordingly purchased some strips of iron, and without, as he says, communicating the fact to anyone, put in small pieces of the iron between the gibs and cotters to tighten up the tie bars. He continued to do this from time to time, and had, he told us, in this way introduced about 150 packing pieces, before the fall of the bridge took place. Whilst so engaged, Mr. Noble also discovered one of the columns under the high girders and three in the northern portion of the line cracked, and he immediately took steps to have them encircled with wrought-iron bands, in a way which seems to have met with the approval of Sir Thomas Bouch.

Mr. Noble's duties.

(94.) It should here be stated that Mr. Noble had no knowledge of ironwork, his special duties were with brick and earthworks; moreover his regular occupation at this time was to superintend the new line of railway, which was to connect Newport with the bridge. His time for taking the soundings seems to have been about the equinoxes, and it was then apparently that he employed himself in putting in these packing pieces; but he was not directed by Sir Thomas Bouch to look after the piers, nor indeed does anyone appear to have been ordered to do so. It was a mere voluntary

act on Mr. Noble's part. Whether Sir Thomas Bouch himself made any inspection of the piers during this time, does not clearly appear; his attention seems to have been more particularly directed to prevent the scour of the river from undermining the foundations.

Did the packing pieces tighten up the tie bars?

(95.) It was contended, however, that, whether this was so or not, the step taken by Mr. Noble in introducing these packing pieces between the gibs and cotters was the proper step to take, and that it had the effect of tightening up the ties and of bringing the columns to their bearings. It was said that the columns, being rigidly bolted down at their bases, would by their own elasticity return to their original position, as soon as the force, which had deflected them from the vertical, had ceased, and that it was then that the ties would chatter, their attachments having been extended; but that, when the packing pieces had been inserted, the tie bars, being shortened, would renew their hold upon the columns. But this argument proceeds upon the assumption that the columns were rigid throughout their whole length and rigidly bolted to their base plates; but this can hardly be said to have been the fact, seeing that the bolt holes of the flanges of the 18-inch columns were conical, and that the holes were considerably larger than the bolts, which would allow a large amount of play. If, too, a column had once got out of shape, it is not easy to see how the merely putting in of a packing piece with a hammer could have brought it, with its superincumbent load, back into position. It is more likely that it would have confirmed it in its distorted form.

Alleged increase of stability by loose tie bars.

(96.) And here it may be well to refer to a somewhat extraordinary statement, which was made by Mr. Stewart, the gentleman who assisted Sir Thomas Bouch in preparing the designs for the bridge, who was his principal adviser during the building, and who has been his right-hand man throughout all these proceedings. Mr. Stewart stated that the loosening of the ties "would add to the strength of the structure," as well as to its stability. Mr. Bidder endeavoured to make out that this suggestion that it would add to "the stability of the structure" had not originated with Mr. Stewart, but that it was due to what he called "the adroitness" of Mr. Trayner. That there may be no mistake on this point, it may be well to quote what the witness said in answer to questions put to him by Mr. Trayner.

19,139. (*Mr. Trayner.*) Without troubling you for that, let me put to yon this question : supposing these ties loosened to the extent of a quarter of an inch, would that have materially affected, in your opiuion, the stability of the structnre ?—Not in the least. I may say it is a very remarkable thing that the loosening of the tics, somewhat beyond what Dr. Pole and I calculated, would add to the strength of the structure, by bringing into play, first of all, the resistance of the columns to bending to a greater extent. It also brings the diagonal ties somewhat more into play.

19,140. Do you mean to say that the looseuing of these ties to the extent of a quarter of an inch would have made the structure more stable than it was when it was newly tightly braced up ?—According to the calculations, as a matter of fact, it would.

19,141. Then it was a mistake to tighten them up ?—You may draw that inference, if you like.

19,142. Is not it the necessary inference from what you have said ?—No, because I think it is not a thing to be depended on. If one extends a quarter of an inch, others may extend half an inch.

19,143. Take the hypothesis that is put to yon, that these tie-bars were giving to the extent of a quarter of an inch, do you say that would add to the stability of the structure, or that it would detract from the stability of the structnre ?—Of conrse you mean this and the one opposite (pointing to the model) ? It would add to the stability of the structure.

(97.) The witness then went on to say, that "if Sir Thomas Bouch could have put " in some kind of spring that would have a yielding of a quarter of an inch, it would " have added to the strength of the structure." He was then asked,—

19,147. That being so, I am curions to kuow whether you can suggest any reason why the structure was made less stable by the tighteuing up of these bars and making the structure as rigid as it was when General Hutchinson saw it ?—No, I do not snppose I cau.

19,148. It was a waste of energy, was not it, to tighten them up when the result was to lessen the stability of the bridge ? You cannot suggest any reasou for that ?—No, it is very hard to answer these philosophical qnestions.

19,149. In a general sense, does not the stability of a bridge depend on the rigidity of its columns, to a large extent at least ?—Certainly.

If Mr. Stewart's theory was correct, the stability of a ship's masts would be increased by the loosening of the shrouds.

Speed of the trains.

(98.) Before we leave the question of maintenance, it may be well to say a few words in regard to the speed, at which trains were allowed to cross the bridge. It has been said that in General Hutchinson's report of the 5th of March there was a recommendation that it would "not be desirable that trains should run over the bridge at a high rate of speed," and he suggested "25 miles an hour as a limit, which should not be exceeded." This seems to have been interpreted by the servants of the Company to mean that from station to station they were not to go at a greater average speed than 25 miles an hour, and this they seem to have done. Seeing,

however, that they had, in approaching the cabin at either end to reduce the speed of the train to some two or three miles an hour in order to take the baton, and had then to mount an incline before reaching the summit, it is obvious that, if they did the distance from cabin to cabin at the rate of 25 miles an hour, they must have been going through the high girders, where it is level and on the summit, at a very much greater speed. No complaint, indeed, was made of the speed of the trains going south, for they had to mount a very steep incline of about 1 in 74 from the north cabin, until they had passed over four spans of the high girders, and then an incline of 1 in 130 for another span before reaching the level on the summit, they had therefore no means of getting up a high rate of speed, until they had got some distance across the high girders. But with the trains going north it was different; starting from high ground on the south shore the roadway falls for the first three spans, it is then level for the next three, after which it rose by a gentle incline at first of 1 in 353, and then of 1 in 490, until it reached the second pier of the high girders, whence it was level for six spans, and then fell for the first span at the rate of 1 in 130, and for the last four spans very rapidly at the rate of 1 in 74. Now the evidence of the engine drivers was that they were getting up speed all the way from leaving the south cabin, and that it was only after crossing the summit, and when they had got on to the incline to the north, that the brake was put on. It is obvious, therefore, that the trains going north must have attained a very high rate of speed before putting on the brake to go down the incline.

Evidence of ex-Provost Robertson.

(99.) But the best evidence as to the speed, at which the trains passed through the high girders, was given by Mr. William Robertson, ex-Provost of Dundee, and who is also an engineer, and therefore able to speak with authority on the subject. He told us that he had frequently timed the trains going north to go from end to end of the high girders in 60 seconds, which would give us, (the distance being 3,149 feet,) a speed of 35·78 miles an hour; and that on two occasions he had timed it to do the distance in 50 seconds, which would be at the rate of 42·94 miles an hour. It was attempted to be shown that the trains referred to could not have attained so great a rate of speed, but it seems to have been forgotten that for the last five spans of the high girders on the north there is an incline at first of 1 in 130, and for the last four spans of 1 in 74, in going down which of course almost any speed could have been obtained. As a proof that ex-Provost Robertson thought the speed dangerous, it may be mentioned that, although he had a season ticket to go both ways between Dundee and his residence at Newport, he ceased before the bridge fell to travel northward, while still continuing to use it going southward.

Effect of putting on brake on north section of high girders.

(100.) And here it may be mentioned that, according to the evidence of the engine drivers, the brake was generally put on, when going north, at about the third or fourth span from the end of the high girders, that is to say, when they had got on to the northern section, and were descending the steep gradient of 1 in 74. Now, without going quite the length of saying with Mr. Bidder that the *vis viva*, which would thus be lost, must ultimately be transmitted absolutely undiminished to the lowest pier, there can be no doubt that, applying the brake, when the train was at its highest speed, must have put a very severe strain on the piers, which would have been carried down the columns to their bases; and as this generally took place, when the train was on the northern section of the high girders, and would be repeated by every train going north, the columns of this section would, by being subjected to these heavy strains, be weakened, and would probably be the first to give way. These considerations give some strength to the statement, to which the evidence seems to point, that it was the northern section which went first.

True Cause of the Fall of the Bridge.

Badly constructed, and badly maintained.

(101.) Although then this bridge, if properly constructed in accordance with the plans and specifications, might, as we are told, have been capable of resisting a lateral pressure of from 60 lbs. to 70 lbs. per square foot, and a very much greater wind pressure than was probably brought to bear upon it on the evening of the 28th of December; it by no means follows that, constructed and maintained as we have seen it to have been, a very much lower pressure would not have sufficed to blow it down. With its conical bolt holes in the lugs and in the flanges of the 18-inch columns;—with its lugs, shown by experiment to be unable to bear more than one-third of the pressure due to their sectional areas;—with the wind ties, by which the columns were held in position, loose;—with no effective supervision of these cast-iron columns and their attachments to see that they were doing their work properly;—with all these and the other defects,

to which we have called attention, can there be any doubt that, what caused the overthrow of the bridge, was the pressure of the wind, acting upon a structure badly, built, and badly maintained.

(102.) What probably occurred was this. The bridge had probably been strained partly by previous gales, partly by the great speed at which trains going north were permitted to run through the high girders. The result would be that, owing to the defects, to which we have called attention, the wind ties would be loosened; so that, when the gale of the 28th of December came on, a racking motion would be set up between the two triangular groups, into which the six columns forming each pier were divided. This would bring a great additional strain upon the wind ties between the 15-inch columns which connected the two groups of columns together, and which would receive comparatively little support from the ties between the outer 18-inch and the two nearest inner columns, owing to the angle which they made with the line of pressure. The strain, too, upon the lugs being greater, as you descended the columns, the places, at which the columns would naturally give way, would be near their bases; unless, indeed, a weaker spot should display itself higher up, as appears to have been the case in piers 29 and 30, where the two lowest and the lowest tiers respectively are still standing. Whether, indeed, the lugs or the bolts went first, it is impossible to say; but as soon as one went, an additional strain would be brought upon the other, and the columns being thus without support, would naturally fall over to leeward, as some of the witnesses described it, like a pair of rulers. *Racking motion set up.*

(103.) That the separation took place near the base of the columns seems clear from the position, in which the three sections of the high girders were found lying in the bed of the river, each describing an arc, with its concave side towards the piers, being furthest off where there was a fixed bearing, and nearest where there was an expansion joint; which is what might naturally be expected, if the fracture occurred near the base; for the girder, being free at the expansion joints, would much more readily slip off the top of the columns and fall to the bottom as the bridge inclined; whereas, at the fixed bearings it would be held on, and so carried further out. The fact, too, that opposite to pier 29 the girder is nearer to the piers, than it is at the next expansion joint, seems to confirm this view; for the fracture in that case took place, as we have seen, above the second tier from the base, so that at that pier the columns would have five tiers instead of seven on which to turn, and would consequently not be carried so far out. *Separation near the base of the columns.*

Defects in the Design.

(104.) Apart, however, from all these defects in the construction, to which we have called attention, which are sufficient in our opinion to account for the fall of the bridge, the question remains, whether there are not some defects in the design which must sooner or later have brought it down. We were told, indeed, that it was no part of our duty to say how or in what manner the bridge could have been strengthened, that there were a hundred ways in which it could have been done, but that this was not the question, and that all that we had to do was to say, whether it was strong enough. A bridge, however, which with good materials and workmanship is computed to be able to bear only from 60 lbs. to 70 lbs. of lateral pressure per square foot, and which may be subjected at any moment to a wind pressure of from 40 lbs. to 50 lbs., can hardly be said to be sufficiently strong; for there may be latent defects in the material or the workmanship, for which we are told that it is usual to allow a factor of safety of 4 or 5; and it is therefore not right to build a structure with so narrow a margin of safety. We shall therefore proceed to point out what are, in our opinion, the defects in the design, which it will be necessary to avoid if the bridge is to be reconstructed. *Insufficient margin of stability.*

(105.) And first it is very greatly to be regretted that Sir Thomas Bouch, when he was designing the bridge, did not take greater pains to ascertain the nature of the foundations, on which the piers were to rest. It is said that he was deceived by the borers, not of course designedly, for they would have no object in so doing. But what right had Sir Thomas Bouch in a matter of so much importance to trust solely to the word of the borers? It is idle to suppose that, if he had looked at the core which was brought up, he would not have been able to ascertain, whether it was the same rock, which is to be found on each side of the river, or that a bed of conglomerate could have been mistaken for it. And if he had found that they had come upon a bed of conglomerate, it was his duty to have pierced it with a view of ascer- *Mistakes in the borings.*

F 4

taining whether it was capable of supporting the brick piers, on which he designed to place his bridge. Had the solid rock existed, as was too hastily supposed, at a reasonable depth below the bed of the river, so that brick piers could have been built up from the bottom, no doubt the bridge would have been standing at the present day. On the other hand, had it been known that below this thin bed of conglomerate the bottom was only soft sand and mud, either a different design would have been made, or the bridge would have been carried across at some more favourable spot. The mistake, in our opinion, was a very grave one, and for which there is no excuse.

Wider base advisable.

(106.) The next question to be considered is, whether the hexagonal form of the pier, and the way in which the columns were arranged upon it, was calculated to give the requisite amount of stability to the structure. To use General Hutchinson's words —"no one can say that a broader base would not be a desirable thing." Now, in what way could this additional base have been given?

Caissons.

(107.) And first, as regards the caissons. They were, as we have seen, 31 feet in diameter. There seems, however, to be no reason why they should not have been constructed in an elliptical form, say 34 feet long by 28 feet broad, which would have given about the same bearing surface for a foundation, would have been more easily sunk in the river from offering a less resistance to the stream, and would have afforded a much longer base east and west, on which to build the piers which were to carry the columns.

Hexagonal form of piers.

(108.) Again, the hexagonal arrangement of the columns with two outer and four inner columns was not advisable. As has been already pointed out, owing to the girders, which formed the sides of the bridge, being placed midway between the outer and the two next inner columns, the two outer columns had to bear as much as the four inner columns together, or half the superincumbent weight, so that each of the outer columns had to bear one quarter of the weight, whereas the inner columns had only to bear one eighth of it; added to which the outer columns had to bear the greater part of the lateral wind pressure. And although the inner columns were 15 inches, whilst the outer ones were 18 inches in diameter, this was by no means sufficient to compensate for the extra strains, which the outer columns had to bear; and it certainly seems that it would have been better to have had two outer columns instead of only one on each side. It would have given a wider base, and therefore increased stability to the structure; it would also have had this advantage, that if one of the outer columns had failed, the bridge would not necessarily have fallen, whereas with only one outer column on each side, the failure of any one of them would cause it to fall at once. This consideration seems not to have been disregarded by Sir Thomas Bouch, when building the Beelah Viaduct, for although in that structure there were only six columns to each pier, they were arranged in two parallel lines across the bridge, four of them as outer and raking columns, and two only as inner ones, the converse of the arrangement in the Tay Bridge, where there were only two outer and four inner ones. It certainly therefore appears that it would have been better, if in building the Tay Bridge there had been eight columns to each pier, arranged like those in the Beelah Viaduct in two parallel lines, and with two outer columns on each side and four in the centre; and this arrangement seems at one time to have been intended. Why it was not carried out, has not in our opinion been satisfactorily explained.

Caisson sufficient to support eight columns.

(109.) It was said indeed that the caisson, with a diameter of 31 feet, would not have borne a pier, which would have carried the columns in the way suggested; but a glance at the plan will show that this is not the case, and that a pier might easily have been constructed, which would have carried the eight columns in two parallel lines, and with the outer columns placed at the same distance from each other, as the outer columns were in the bridge as actually constructed, namely, 21 feet 10 inches from centre to centre. Indeed, it was admitted by Mr. Gröthe (Q. 13,667) that they had ample space on the top of the caisson for building up brickwork sufficient to support eight columns. It was objected, however, by Sir Thomas Bouch, that in that case the outer columns would have had their foundation on the brick rim of the caisson, whilst the inner columns would have rested on the concrete, and that that would not have been safe, brickwork and concrete not being, as he said, homogeneous. Sir Thomas Bouch, however, could hardly have remembered, when giving this answer, that the hexagonal piers, which carried the columns, were faced in the lower part with brick and in the upper part with stone, and that the whole rested on the concrete of the caisson, the centre of the hexagonal pier being also filled with concrete. We do not therefore think that there is much in this objection.

(110.) Another advantage, which would have resulted from the columns being arranged in two parallel lines of four each, would have been that the wind ties connecting the outer with the next inner columns would have acted directly in the line of the pressure; instead of as in the actual structure at an angle of 45°, so that they gave very little support to the inner columns. *Outer wind ties.*

(111.) Another great objection to the design was that the ⊾ girders, which covered the tops of the two triangular groups of columns, were not connected, as they should have been, so as to have formed a continuous girder over the tops of all the columns. This would have given great additional stability to the structure by binding all the columns together. As it was, the two groups were held together merely by the struts and ties between the columns, which were therefore liable to get out of shape. There was not a witness, we believe, unless it was Mr. Stewart, who did not say that the connexion of the two ⊾ girders at their ends would have given increased stability to the structure. *The ⊾ girders.*

(112.) Another defect in the design was the omission of the spigot upon the lower tier of columns, in consequence of which there was nothing but the pinching action of the flange bolts to prevent the columns from shifting their positions on the base pieces. It was said by Mr. Baker that the mere weight of the columns with the load, which they bore, would produce such an amount of friction as to render them immovable on their base pieces, but he clearly overlooked the fact that, according to the calculations of Dr. Pole and Mr. Stewart, a pressure of 20 lbs. of wind would suffice to relieve the outer windward columns of all pressure, and to bring a tensile strain to bear upon the flange bolts. *Omission of spigot at base.*

(113.) But the greatest defect of all was in the cast-iron lugs, to which the ties and struts were attached, and in providing not only that they should be cast with the columns, but with the holes ready made. It is to this, and to the casting of the holes in the flanges of the 18-inch columns, and to not seeing that these holes were made properly cylindrical, and that the bolts fitted them accurately, that the weakness of the piers and the fall of the structure is mainly due. We have dwelt at length on these points, whilst discussing the question of construction, but they belong also to this part of the subject, for it was part of the design that they should be so cast. *Cast-iron lugs, and holes.*

Comparison of Tay Bridge and Beelah Viaduct.

(114.) But perhaps the best way of showing the defects of the Tay Bridge will be by comparing it with another somewhat similar work erected by Sir Thomas Bouch some time before; we refer to the Beelah Viaduct, situate about four miles from the town of Brough, and which carries the South Durham and Lancashire Railway across one of the wild mountain gorges in Westmoreland. The description of this viaduct is taken from a work by Mr. William Humber, entitled "A complete Treatise on Cast and Wrought Iron Bridge Construction." The viaduct, which is 1,000 feet long, is carried on "15 piers of varying heights, according to the section of the valley," each of the spans being 60 feet from centre to centre. Each pier was composed of "six hollow "columns, placed in the form of a tapering trapezium, and firmly bound together with "cross girders at distances of 15 feet perpendicular, and by horizontal and diagonal "wrought-iron tie bars." The columns, which as we have already stated, are arranged in two parallel lines of three each, have an extreme distance of 50 feet from centre to centre on the base, tapering towards each other as they ascend, until at the top immediately under the platform girders, they are 22 feet apart from centre to centre. "The taper" we are told, "is given in the foundation piece at the base of each column, "which foundation piece is firmly bolted to a stone base, the upper surface of which "is bevelled at such an angle, as will produce the taper required for the columns. "Thus the columns have all their flanges square to the centre line, which simplified "the fitting very materially. The depth of the stone foundations, varied according to "the nature of the ground, and the height of the piers, but in almost all cases they "went down to the solid rock." *Description of Beelah Viaduct.*

(115.) "We are told that "it is a distinguishing feature in this viaduct, that the "cross, or distance girders of the piers encircle the columns, which are turned up at "that point, the girders being bored out to fit the turned part with great accuracy. "No cement of any kind was used in the whole structure, and the piers when com- "pleted, and the vertical and horizontal wrought-iron bracings keyed up, are nearly "as rigid as though they were one solid piece." Further on the author says, "The "fitting was all done by machines, which were specially designed for the purpose, "and finished the work with mathematical accuracy." *Cross girders.*

Flanges and holes.

(116.) " The flanges of the columns were "all faced up and their edges turned, " and every column was stepped into the one below it with a lip about $\frac{5}{8}$ of an inch " in depth, the lip and the socket for it being actually turned and bored. That portion " of the column against which the cross girders rested was also turned. The whole of " these operations were performed at one time, the column being centred in a hollow " mandril-lathe. After being turned the columns passed on to a drilling machine, in " which all the holes in each flange were drilled out of the solid simultaneously. And " as this was done with them all in the same machine, the holes, of course, perfectly " coincided when the columns were placed one on the other in the progress of erection. " Similar care was taken with the cross-girders, which were bored out at the ends by " machines designed for that purpose. Thus, when the pieces of the viaduct had to " be put together at the place of erection, there was literally not a tool required, and " neither chipping or filing to retard the progress of the work."

Comparison of the two structures.

(117.) It is true that at the deepest part this viaduct stood 195 feet above the ground. Look at it, however, with its spans of 60 feet each;—its columns, of which four are outer raking columns, with a base of 50 feet, tapering up to 22 feet at the top;—its horizontal cross-girders encircling the columns at every 15 feet;—its holes all carefully drilled, and all the work done with mathematical accuracy by machines designed for the purpose. And compare it with the Tay Bridge, with its spans of 245 feet;—its six columns, with a taper of 12 inches in a height of more than 80 feet, and with only one instead of two raking columns on each side;—its cast-iron lugs with the holes cast with them, to which the ties and struts were attached;—its two L girders unconnected with each other;—its conical bolt-holes in the flanges of the outer columns. And the only conclusion to which we can come is, either that the former was extravagantly strong, or the latter inordinately weak.

Reasons given by Sir Thomas Bouch for deviating from the plan of Beelah viaduct.

(118.) Sir Thomas Bouch was asked by Mr. Barlow, why he deviated from the plan which he had adopted in the Beelah Viaduct, and he then gave the following rather remarkable evidence.

17,214 (*Mr. Barlow.*) Do you remember what description of horizontal ties were used in your Beelah viaduct?—Yes.

17,215. What did the horizontal ties consist of; from the drawing I have seen they appear to consist of girders placed quite across between the columns?—That is from column to column; yes, and the ties go into them.

17,216. In this structure you departed from that construction?—Yes.

17,217. Why did you depart from that construction?—I can only tell you this, that I had a different idea of the force of the wind at that time before I got the report on the Forth Bridge.

17,218. (*The Commissioner.*) Is that the only reason why you did away with those ties?—They were so much more expensive; this was a saving of money.

(119.) Mr. Humber says that the Beelah Viaduct was one of the lightest and cheapest of the kind, that has ever been erected. Apparently, however, Sir Thomas Bouch was of opinion that a lighter and cheaper structure would do for the Tay Bridge, although one span of the latter was more than equal to four spans of the viaduct, so that for the same length of girder, for which 30 columns were considered necessary in the viaduct, the Tay Bridge had only 12, and those of a very inferior construction.

Responsibility for the Accident.

Responsibility of Sir Thomas Bouch.

(120.) The conclusion then, to which we have come, is that this bridge was badly designed, badly constructed, and badly maintained, and that its downfall was due to inherent defects in the structure, which must sooner or later have brought it down. For these defects both in the design, the construction, and the maintenance, Sir Thomas Bouch is, in our opinion, mainly to blame. For the faults of design he is entirely responsible. For those of construction he is principally to blame in not having exercised that supervision over the work, which would have enabled him to detect and apply a remedy to them. And for the faults of maintenance he is also principally, if not entirely, to blame in having neglected to maintain such an inspection over the structure, as its character imperatively demanded. It is said that Sir Thomas Bouch must be judged by the state of our knowledge of wind pressures, when he designed and built the bridge. Be it so, yet he knew or might have known that at that time the engineers in France made an allowance of 55 lbs. per square foot for wind pressure, and in the United States an allowance of 50 lbs. And although there seems to have been no agreement amongst English engineers as to the allowance proper to be made, Mr. Brunlees told us that he allowed 30 lbs., and even Mr. Baker allowed 28 lbs. Sir Thomas Bouch was building a bridge on somewhat new principles, and in a position where it would be peculiarly exposed to the action of westerly and south-

westerly gales; and not only does he make no allowance for wind pressure, but actually builds the bridge weaker and lighter and with wider spans, than in his previous works. To have built and designed a bridge which, if properly constructed in all respects, would only have borne a lateral pressure of from 60 lbs. to 70 lbs. per square foot, when a pressure of 40 to 50 lbs. of wind was quite possible, was a grave error of judgment. Whether, too, the calculation of its stability, or the maximum pressure of the wind be or be not erroneous, matters very little; the bridge fell in a gale of wind which, though violent, was not one, which could not and ought not to have been provided against; it fell solely by the action of the wind; either then the margin of safety was too low, or the defects too great. In neither way can Sir Thomas Bouch escape his responsibility.

(121.) We think also that Messrs. Hopkins, Gilkes, & Co. are not free from blame for having allowed such grave irregularities to go on at the Wormit foundry. Had competent persons been appointed to superintend the work there, instead of its being left almost wholly in the hands of the foreman moulder, there can be little doubt that the columns would not have been sent out to the bridge with the serious defects, which have been pointed out. They would also have taken care to see that the bolt-holes in the lugs and flanges of the 18-inch columns were cast truly cylindrical, or, if that could not be done, they would have called the attention of the engineer or his assistants to the fact; but that does not appear to have been done. The great object seems to have been to get through the work with as little delay as possible, without seeing whether it was properly and carefully executed, or not. *Responsibility of the Contractors.*

(122.) The Company also are in our opinion not wholly free from blame for having allowed the trains to run through the high girders at a speed greatly in excess of that, which General Hutchinson had suggested as the extreme limit. They must or ought to have known from the advertised time of running the trains that the speed over the summit was more than at the rate of 25 miles an hour, and they should not have allowed it, until they had satisfied themselves, which they seem to have taken no trouble to do, that that speed could be maintained without injury to the structure. *The Railway Company.*

(123.) It remains to inquire whether the Board of Trade are also to blame for having allowed the bridge to be opened for passenger traffic, as and when they did. Let us see then what are the duties which the Legislature imposes upon the Board of Trade in connexion with the opening of new lines of railway, and how those duties were performed in this case. *The Board of Trade.*

(124.) By the Act 5 & 6 Vict. c. 55, s. 4, it is enacted that no new line of railway shall be opened for passenger traffic, until one month after notice of the company's intention to open it has been sent to the Board of Trade, and until 10 days after notice has been sent that it is complete and ready for inspection. No plans or drawings of the structure are required to be sent before the service of the notices, and as a fact we are told that they are seldom sent before the 10 days' notice is served, and frequently not until afterwards. One of the inspecting officers of the Board of Trade has then to examine the plans and details, to inspect the railway, and to make his report; and if a copy of his report and an order to postpone the opening are not sent to the railway authorities before the expiration of the 10 days' notice, the company may open the line for passenger traffic without the sanction of the Board of Trade, whatever may be its then state and condition. Seeing too that the inspecting officers may, when the notice reaches them, have other work on their hands, it is obvious that the examination and inspection can be little more than superficial. *Its powers in these cases.*

(125.) It seems that on the receipt of the usual notices from the North British Railway Company of their intention to open the Tay Bridge for passenger traffic, Major-General Hutchinson, one of the railway inspectors for the Board of Trade, was instructed to inspect the bridge. The inspection took place, as we have stated on the 25th, 26th, and 27th of February 1878, and on that occasion the company placed at General Hutchinson's disposal, for the purpose of testing the bridge, six new goods engines, each of which weighed 73 tons, and measured $48\frac{1}{2}$ feet over all; and as the total weight of the six engines was thus 438 tons, and the total length 291 feet, this gave a pressure of rather more than $1\frac{1}{2}$ tons to every running foot, which is considered a very severe test. These engines were run singly and together over the bridge at various speeds up to 40 miles an hour, and the extent of the deflection and of lateral oscillation having been carefully noted, the results, to use General Hutchinson's words, were considered satisfactory, the bridge having been found to be stiffer than he had anticipated. Accordingly, on the 5th of March following he reported that he saw "no reason why the Board of Trade should object to the railway on the Tay Bridge being used for passenger traffic." *Course taken in the present case.*

General Hutchinson saw no reason to withhold a Certificate.

(126.) In giving his evidence before us, General Hutchinson was asked, (Q. 15,967) whether his examination of the bridge on that occasion had been sufficient to enable him to make his report, and he answered, "It was. I observed no symptoms of "weakness, which in my judgment gave any reason to doubt the stability of the "structure, of course always presupposing that the materials of which it was con- "structed were good, that the workmanship was good, and that it was properly "maintained." Mr. Bidder, not being satisfied with this answer, and anxious to obtain a stronger expression of opinion from him on the subject, asked him, (Q. 15,989) "I think I gather that in your judgment, assuming it to be properly constructed, and the workmanship to be good, the design was satisfactory;" but General Hutchinson answered, "I would rather put it in this way; that the design was not unsatisfactory; "there was nothing in the design in my judgment to warrant me in objecting in any "way to it. Of course no one can say that a broader base would not be a desirable "thing." General Hutchinson declined to pledge himself to a general approval of the design; all that he would say was that he could see nothing in it, which would justify him in taking the very strong measure of withholding a certificate. So also with respect to the materials and the workmanship, he declined to say whether they were good, nor was it possible for him to do otherwise, seeing that the whole of the work was finished, and the defects, if any, covered up, when General Hutchinson made his inspection. He admitted very fairly that his inspection had been only a superficial one, and that he could judge of the work only from its appearance externally.

Limits of the Board's powers.

(127.) It is important to bear this in mind, for there seems to be an impression abroad that, after a work has been inspected and passed by the officers of the Board of Trade, the engineer and others, by whom it has been constructed, are relieved from responsibility for any defects, which may subsequently be discovered; but this can hardly be so. If the inspecting officers are to be held responsible for all defects both of design and of construction, not only should the plans be submitted to them for their approval before the work is commenced, but they ought during its progress to be allowed to exercise the same amount of supervision, as the engineer and his assistants are supposed to do. Whether the country would be prepared to sanction any such interference with private enterprise, with the view of relieving those, who are and ought to be primarily responsible for the work, may well be doubted; but however this may be, the Legislature has not done so. All that the law requires is that the officers of the Board of Trade shall say, not whether the design is good, and the work constructed on the best principles, nor whether there are or are not any latent defects in it, but whether they can give any good reason why it should not be opened for passenger traffic.

General Hutchinson made no allowance for wind pressure.

(128.) One point, however, deserves to be noted in connection with General Hutchinson's inspection, and it is this, that, although he seems to have tested the bridge sufficiently, indeed severely, for a vertical dead weight pressure, he made no allowance of any kind for wind pressure, it not being, he said, the practice to do so. It may be well to quote what he says on this subject:—

16,070. (*The Commissioner.*) Did you make any calculations at all when these plans were given to you, as to what force of wind would be sufficient to overturn the bridge?—No, I did not. I made no calculations as regards the wind.

16,071. How did you judge then of the stability of the bridge, if you made no calculations?—As I have already stated, the subject of wind pressure never entered into the calculations that I made, and never had done, I believe in, I will not say, civil engineers' calculations, but as far as I know, it has never been taken into account.

16,072. Do you know whether it is so in America or in France?—I cannot say. I believe that in France they have some rules, but it has never been hitherto customary in this country, as far as I am aware, to consider this question, especially in an open structure like this. Had the girders been plate girders, it would, of course, have struck one naturally that one ought to take very great care about the wind.

(129.) Further on he said, in answer to a question put by Mr. Barlow—

16,084. With regard to the width of base, if everything was made strong and good, with proper holding down bolts, and with very sufficient wind ties, do you think that width of base insufficient?—No, I think not insufficient, if everything was thoroughly good and made as solid and substantial as possible. There would be, I should imagine, quite 60 lbs. or 70 lbs. of stability against lateral pressure, supposing these piers were as one, and the holding-down bolts good. I have not made the calculation with regard to the holding-down bolts; I have made it with regard to the piers standing on their legs, and I make it something over 40 lbs., without taking in the holding-down bolts.

(130.) When General Hutchinson gave his answer that he considered that 60 lbs. or 70 lbs. of stability would not be insufficient, he could hardly have known that a wind pressure of 40 lbs. and even 50 lbs. was quite possible, which would leave a margin of stability of only about half. After what has come out in the course of this

inquiry, it is clear that there can be no justification in future for disregarding altogether, as seems to have been done, the effect of wind pressure on such a structure as this; but whether General Hutchinson is or is not to blame for having so done, Sir Thomas Bouch is not relieved from his responsibility.

Standing portion of the Bridge.

(131.) It remains for us to say a few words in regard to the portion of the bridge which is still standing, and on which we have had a report from Mr. Law, which will be found in the Appendix.

(132.) Mr. Law, after calling attention to the bed of the river, which he states still shows a tendency to scour, and will therefore require to be carefully watched, observes that on piers 15 to 27 to the south of the high girders, and piers 42 to 48 to the north thereof, the weight of the superstructure is wholly borne "by four " 16-inch columns, which are bolted to a foundation stone, and are surmounted by a " square wrought-iron box girder or entablature, which supports the superstructure." In addition to which there are two outer columns, one on each side, which are carried up vertically to the last tier, and then rake inwards at a very sharp angle to form raking struts to the wrought-iron box girder. But, as Mr. Law observes, "it is " evident that in their present condition these external columns are of very little " service in strengthening the structure," (and we would add in resisting wind pressure), " first, because of the very unfavourable angle of the wrought-iron ties, which connect " them with the 16-inch columns, and secondly, because they have no direct tie at the " upper part of the perpendicular columns to resist the thrust of the raking columns."

(133.) He also calls attention to a number of other piers on the north side of the bridge, where there are but three columns, two vertical and one raking, "upon " which the lattice girders of the superstructure merely rest without any attach- " ment." These three columns were, he says, "intended to be," and ought to be, " in one plane;" but they are not always so. The lengths, too, of the lattice girders not corresponding to the distances between the centres of the piers, the joints of the girders are not vertically over the centres of the piers, deviating in some instances to the extent of 18 inches. The result is, there being "no kind of stay to prevent the " movement of the head of the column in the direction of the length of the " bridge, and no kind of attachment between the girder and the columns," that there is very great risk of the girder, which here merely rests on the tops of the columns, slipping off.

Conclusion.

(134.) These are some of the defects in the standing portion of the structure, to which it is necessary that attention should be directed, in the event of its being determined to restore the bridge. That it will be rebuilt there can be no doubt, for the interests of the large and thriving town of Dundee imperatively demand it. If, however, it should be rebuilt with its narrow base, its cast-iron lugs, its conical bolt-holes, its unconnected L girders, and with the other numerous defects, which we have pointed out, and without adequate allowance being made for wind pressure, a very serious responsibility will rest on all concerned, and one which the country would not very readily pardon.

The two Reports compared.

(135.) I stated in the commencement of this report that there was practically an entire agreement between my colleagues and myself in the conclusions, at which we had arrived; and that almost the only difference between us was, whether some facts, which had come out in the course of the inquiry, ought or ought not to be referred to more at length.

(136.) The points, on which we are agreed, are as follow:—I agree with them in thinking; *Points on which we are agreed.*

(1.) That there is no evidence to show that there has been any movement or settlement in the foundations of the peirs.

(2.) That the wrought iron was of fair quality;

(3.) That the cast-iron was also fairly good, though sluggish in melting;

(4.) That the girders were fairly proportioned to the work they had to do;

(5.) That the iron columns, though sufficient to support the vertical weight of the girders and trains, were, owing to the weakness of the cross bracing and its fastenings, unfit to resist the lateral pressure of the wind;

(6.) That the imperfections in the work turned out at the Wormit Foundry were due in great part to a want of proper supervision;

(7.) That the supervision of the bridge after its completion was unsatisfactory;

(8.) That, if by the loosening of the tie bars the columns got out of shape, the mere introduction of packing pieces between the gibs and cotters would not bring them back to their positions;

(9.) That trains were frequently run through the high girders at much higher speeds than at the rate of 25 miles an hour;

(10.) That the fall of the bridge was probably due to the giving way of the cross bracing and its fastenings.

(11.) That the imperfections in the columns might also have contributed to the same result.

These are the points, neither few nor unimportant, on which I concur with my colleagues.

Facts not dealt with by my colleagues.

(137.) The points, on which we are not agreed are, as to whether some facts, which have come out in the course of the inquiry, ought or ought not to be mentioned. The following are some of the facts, to which I refer.

The borings.

(138.) In the first place, I think that the error in the borings ought not to be passed over in silence. It is said that engineers are always liable to be deceived by the borers, and that therefore Sir Thomas Bouch could not be held to blame on that account. But that argument does not satisfy me. I should have thought that, if engineers are liable to be deceived by borers, it is all the more important that, before designing a bridge, they should satisfy themselves, beyond a doubt, of the accuracy of the borings, and which there would have been no difficulty in doing in the present case. It is also said that, as no movement or settlement was found after the accident to have occurred in the foundations, the error in the borings was not important. But that also does not satisfy me; for it is clear that the error in the borings led to the alteration of the piers from brickwork to iron columns, and that that undoubtedly was the cause of the casualty.

The striking the girder.

(139.) Secondly, I think that we are bound, in justice to those most deeply interested in this case, carefully to consider all the various suggestions which they have put forward to account for the fall of the bridge; and it therefore seemed to me that it would not be fair to them or satisfactory to you, that we should simply give it as our opinion that the train had not struck the girder, without stating at length the grounds on which that opinion was formed.

The supervision.

(140.) I think also that it is not sufficient to say that the supervision at the Wormit Foundry, and in the subsequent maintenance of the bridge was insufficient, without saying in what that insufficiency consisted, and who was to blame for it.

Defects in the design.

(141.) I think also that it was our duty to call attention to certain defects in the design, which rendered the structure weak, and thereby contributed to its fall; for instance, to the narrow base, the slight inclination of the outer columns, and the omission of the spigots at their bases, and to the casting of the holes in the lugs and in the flanges of the 18-inch columns. I thought also that these defects could best be shown by comparing the work on the Tay Bridge with that done by the same engineer on the Beelah Viaduct.

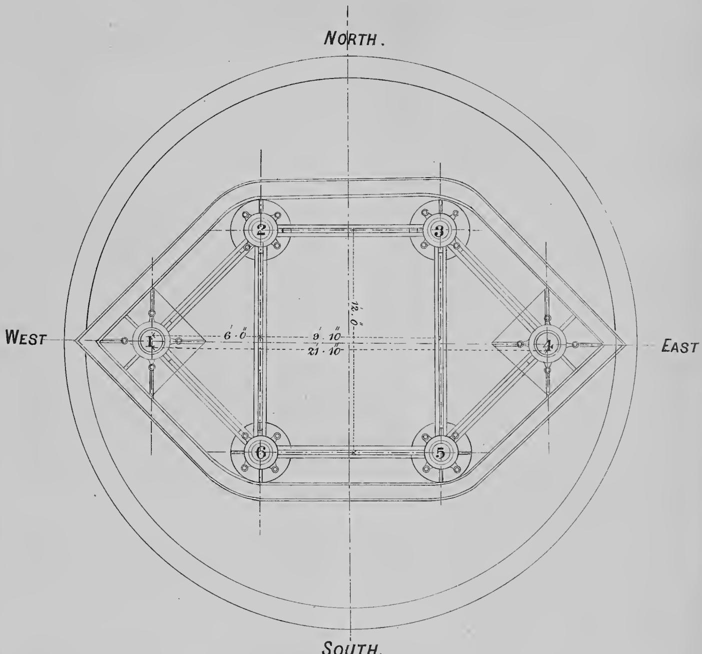
Responsibility for the casualty.

(142.) It seemed to me also that we ought not to shrink from the duty, however painful it might be, of saying with whom the responsibility for this casualty rests. My colleagues thought that this was not one of the questions that had been referred to us, and that our duty was simply to report the causes of, and the circumstances attending, the casualty. But I do not so read our instructions. I apprehend that, if we think that blame attaches to any one for this casualty, it is our duty to say so, and to say to whom it applies. I do not understand my colleagues to differ from me in thinking that the chief blame for this casualty rests with Sir Thomas Bouch, but they consider that it is not for us to say so.

Wind pressures.

(143.) Lastly, my colleagues in their report call attention to the fact "that there is no "requirement issued by the Board of Trade respecting wind pressure, and that there "does not appear to be any understood rule in the engineering profession regarding "wind pressure in railway structures;" and they therefore "recommend that the "Board of Trade should take such steps as may be necessary for the establishment of "rules for that purpose." I cannot, however, join in that recommendation; for it appears to me that, if there is no "understood rule in the engineering profession

SECTIONAL PLAN OF THE BASE OF ONE OF THE FALLEN PIERS.



Scale 3/16ths. of an Inch to a Foot.

" regarding wind pressure in railway structures," it is for the engineering profession, and not for the Board of Trade, to make them. I will add that, if I rightly understood my colleagues at our last interview, they concurred in the conclusions, to which I had come, that there might be a maximum wind pressure of from 40 lbs. to 50 lbs. per square foot, and this too not only over a few feet, but over the whole extent of a span of one of the high girders, and I gather as much from their Report. And if so, seeing that it is the practice in France to allow 55 lbs. per square foot for wind pressure, and in the United States 50 lbs., there seems to be no reason why a similar allowance should not be made in this country.

(144.) I will only add, in conclusion, that I should hardly have ventured, in a case of so much difficulty and importance, to have made on my own responsibility the remarks I have done, had I not felt that they are fully borne out by the evidence, that has been laid before us; and that, although my colleagues have not thought fit to join in this Report, they do not differ, except perhaps on some very minor points, from the conclusions, at which I have arrived.

I have the honor to be,
Sir,
Your most obedient, humble Servant,

H. C. ROTHERY.